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Economics and Air Pollution

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Abstract

This chapter discusses the relationship between economics and air pollution: first, it presents the main characteristics of the economic growth-environmental pressure debate and introduces the concept of environmental Kuznets curve hypothesis (EKC). As an example of the EKC, the estimated relationship between CO_2 emissions and economic growth, using a cross-sectional sample of 152 countries, is reported. Second, the chapter discusses air pollution as a result of a market failure and introduces the main theoretical causes of ambient degradation, acknowledging air pollution externalities as a common problem that leads to overexploitation in the absence of well-defined property rights for the atmosphere. Third, the main instruments for pollution control, including traditional regulation based on standards and the more flexible incentive-based regulation, are presented. Finally, the chapter reviews the main features of cost and benefits related to air pollution emissions.

Keywords: air pollution, air quality, incentive-based regulations, transferable permits, air quality standards, cost-benefit analysis

1. Introduction

Most marketable goods are produced by the manufacturing sector. Industry is, with no doubt, one of the main contributors of economic growth, and its products are the bases of today's lifestyles. The extraction of raw materials from natural resources is part of a transformation process where industries introduce both final products and pollution to society. In 2013, the proportion of value added from manufacturing (VAM) to the gross domestic product varied from 8.6% in low-income countries to 20.8% in middle high-income countries (see **Table A1** in Appendix). Nonetheless, in the information era, traditional manufacturing is no longer the most important sector of the economy. The world average VAM has decreased from 19.2 to 16.3%

during the period 2000–2013. This trend of the VAM is observed in both low-income and high-income countries, possibly explained by a more integrated industry to the services' sector and the emergence of the so-called information economy.

Notwithstanding the trend described above, the negative effects of industrial activity on the environment, which once were perceived exclusively as a local pollution problem, today are widely debated in public policy, aiming not only to preserve the environment, but also to mitigate and adapt to climate change produced by greenhouse gases. Overall, emissions from CO_2 coming from the industrial manufacturing and construction sectors are higher in low-income countries than in high-income countries. Even though VAM decreased worldwide, emissions of CO_2 from the industrial sector do not seem to follow the same path. While CO_2 emissions represented 18% of the total consumption of fossil fuels in 2000, they reached 20% in 2013 (see **Table A2** in Appendix).

Traditionally, analysts of pollution classify this physical phenomenon into three categories: (1) greenhouse gases such as CO_2 or methane, (2) pollution from chemical imbalances, and (3) aerosols.

Regarding the first category, in Ref. [1], NASA estimates that the global levels of carbon dioxide have increased since 1960 from 316 ppm to near 407 ppm in 2016. As documented in Ref. [2], these high levels of CO_2 have caused the world to increase its temperature, and if the current trend persists, by 2035, we would observe a level of 535 ppm, which makes a global average rise of at least 2°C more likely. Today, strong scientific evidence suggests links between concentrations of greenhouse gases and changes in global temperature: a rising of 2°C relative to preindustrial levels could bring as a result risks in food security, significant changes in water availability, collapse of ecosystems, extreme weather events, and irreversible impacts such as the melting of Greenland ice sheet [2].

Chemical imbalances, on the other hand, create pollution mainly in the form of nitrogen oxides and sulfur oxides, which in turn produce acid rain and smog. Chemical imbalances such as the incomplete combustion of fossil fuels produce carbon monoxide which is known for its toxicity and the concomitant risks for the respiratory and circulatory systems.

Aerosols are essentially suspended particles of different sizes that are produced mainly due to the burning of fossil fuels and industrial processes. Particulate matter affects water systems, agriculture, and also the respiratory system of humans. Most local ambient pollution is attributed to chemical imbalances or to aerosols whose main sources are vehicles or combustion processes in industrial facilities. The World Health Organization (WHO) recognizes that air pollution is a major environmental risk to health. In fact, the WHO estimated that ambient air pollution caused 3.7 million premature deaths in both urban and rural areas worldwide in 2012 [3].

The deterioration of air quality from industrial smokestacks' emissions and other sources that are well beyond the control of individuals has triggered public concerns and has inspired heated debates on the trade-off between environmental quality and economic growth. In this chapter, we discuss first the nature of the debate between growth and environmental quality; second, the theoretical causes of environmental degradation from the perspective of econom-

ics; and, third, the type of economic instruments that economists have proposed to regulate ambient pollution as an alternative to traditional policies based on the so-called command and control approach. Then, we briefly discuss the framework to think about costs and benefits of pollution. In the last section, we discuss some lessons learned.

2. Economic growth and emissions

The relationship between environmental degradation and economic growth has been object of constant debate among environmental economists. During the last two decades, the debate between economic growth and the environment introduced into the discussion the environmental Kuznets curve hypothesis (EKC). Within the framework of the EKC hypothesis, it is expected to observe an inverse U curve relationship between a variable that measures environmental pressure (i.e., air pollution) and economic growth (usually measured as income per capita). The name of environmental Kuznets is related to the bell-shaped relationship between income distribution (inequality) and economic growth that the economist Simon Kuznets suggested in the 1950s. Identifying the patterns of environmental pressure and economic growth allows researchers to understand whether economic growth is part of the solution to environmental problems, or whether, on the contrary, policies aimed to encourage economic growth have detrimental consequences on the environment. As pointed out by De Bruyn and Heintz [4], if we accept the hypothesis of the environmental Kuznets curve, we are recognizing that (1) pollution and environmental degradation is only a temporary phenomenon, and (2) economic growth can be part of the solution to global environmental problems.

Literature on the environmental Kuznets curve is extensive. An overview of some of the most influential empirical studies that have examined the relationship between indicators of environmental pressure and per capita income levels can be found in Ref. [4]. Most studies have used as indicators water and air pollution.

In Ref. [5], the authors examined the relationship between urban air pollution and economic growth. These authors did not find evidence that environmental quality decreases with economic growth. Grossman and Krueger found an inverse U-shaped relationship and calculated the turning points of this relationship.[1] For most pollutants examined, after economies reach US$8000 per capita (in 1985 dollars), environmental pressure starts to decrease.

Ref. [6] overviews the most cited studies during the first half of the 1990s. In particular, it examined the study of Grossman and Krueger mentioned above as well as the estimations from Shafik and Bandyopadhyay [7], Panayotou [8], and Selden and Song [9].

As pointed out by Stern et al. [6], the study in Ref. [7] estimated an environmental Kuznets curve for air pollution measured as total suspended particulate matter, emissions of sulfur oxides, and carbon emissions per capita. In their estimations, these authors found that the EKC hypothesis is accepted for these air pollutants. According to their estimations, the level of

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[1] Turning point refers to the level of income at which environmental pressures start to decline.

income at which air pollution starts to decline is between US$3000 and US$4000. In Ref. [9], the authors tested the EKC for the following air pollutants: SO_2, NO_x, SPM, and CO. They found that all pollutants adjust very well to the EKC except carbon monoxide (CO). The following turning points of income were found in this work: for SO_2 US$8709; for NO_x US$11217; for SPM US$10289; and for CO US$5963. However, coefficients were not statistically significant for the latter. In Ref. [6], Stern et al. refer to the study in Ref. [8] in which the author estimated EKC for air pollution (emissions of SO_2, NO_x, and SPM) with a sample of 54 countries. He found that the turning point for air pollution lies between US$3000 and US$5500, depending on the pollutant used in estimations. Most studies surveyed applied reduced forms of the relationship of environmental pressure and economic growth. It should be noted that the economic model corresponds to a descriptive behavior of what it is expected to be observed within the EKC framework.

The basic model of the environmental Kuznets curve hypothesis describes the pattern of the environmental pressure for different growth levels in the economy. Following the explanation of the relationship between income growth and environmental pressure in Ref. [4], environmental pressure increases faster than GDP during the first stage of economic development. This is identified as the first phase of the EKC. The second phase is characterized by an increase in the environmental pressure but at a lower rate than the increase of GDP. In other words, during the second phase, pollution increases at a decreasing rate until the curve reaches a maximum. The third phase starts at the maximum point of environmental pressure. In this phase, the EKC starts to decrease, and if it continues to decrease when income levels tend to infinity, then economic growth is not linked anymore to environmental pressure. In this case, there is an authentic environmental Kuznets curve, in which the pattern of environmental pressure follows an inverted U-shaped curve. If we observe a certain level of income at which environmental pressure starts to increase again, then we are in the presence of the fourth phase, where there is a period of relinking between income and environmental pressure. Some authors have called the environmental pressure-economic growth relationship an N-shaped curve when this phase is observed.

To illustrate the application for estimating the relationship between economic growth and environmental degradation, the following reduced form was considered:

$$CO_2 = \beta_0 + \beta_1 Y_i + \beta_2 Y_i^2 + \beta_3 Y_i^3 + e_i \tag{1}$$

CO_{2i} is per capita emissions of CO_2 of country i, Y_i is GDP per capita of country i. β_0 is a constant that indicates the average level of CO_2 when per capita income does not influence environmental pressure; β_k indicates the importance of GDP per capita on environmental pressure; and the usual assumption of an error term that is normally distributed with mean zero and constant variance $e_i \sim N(0, \sigma^2)$ holds. Results of Eq. (1), estimated by generalized least squares, are reported in **Table 1**. Descriptive statistics and data sources are presented in **Table A3** in Appendix.

Estimation results suggest that CO_2 emissions follow an N-shaped pattern. As income increases, CO_2 emissions increase until income reaches a turning point. These stages are described by the positive and negative coefficients of the GDP pc and GDP pc squared variables, respectively. This suggests the presence of an environmental Kuznets curve. However, because the coefficient of GDP cubed is statistically different from zero, the estimated relationship between environmental pressure and economic growth suggests the possibility of relinking. In other words, CO_2 emissions increase again at high levels of income. Taking into account the sign of the estimated coefficients and their significance level, we reject $H_0: \beta_1 > 0, \beta_2 < 0 \beta_3 = 0$ and conclude in favor of $H_a: \beta_1 > 0, \beta_2 < 0 \beta_3 > 0$. This suggests that the relationship between CO_2 emissions follows an N-shaped polynomial and not a parabolic (inverted U-shaped) polynomial as the environmental Kuznets curve predicts (see **Figure 1**).

Variable	Parameter estimate	SE	T value	P value
Constant	0.0220	0.1289	0.17	0.8646
GDP pc	0.0016**	0.000182	9.09	<0.0001
GDP pc squared	−6.59E−8**	1.599E−8	−4.12	<.0001
GDP pc cubed	7.52E−13*	3.24E−13	2.32	0.0219

Dependent variable. CO_2 per capita emissions.
*Significant at 5% level;
**Significant at 1% level.
$R^2 = 0.2295$.

Table 1. GLS estimation for model (1).

The results from model in Eq. (1) are useful to determine the income level for which the relationship between environmental pressure and economic growth starts to decline given that the turning point is a maximum.

To calculate the turning points, we set up the first derivative of the fitted cubic polynomial equal to zero and solve for Y. Therefore, given in Eq. (2):

$$CO_2 = \beta_0 + \hat{\beta}_1 Y_i + \hat{\beta}_2 Y_i^2 + \hat{\beta}_3 Y_i^3 \tag{2}$$

the first-order condition for maximum (minimum) is given in Eq. (3):

$$\frac{\partial CO_2}{\partial Y} = \hat{\beta}_1 + 2\hat{\beta}_2 Y_i + 3\hat{\beta}_3 Y_i^2 = 0 \tag{3}$$

By solving Eq. (3) for Y_i, we find the turning points. The fitted model suggests that CO_2 per capita emissions will follow an N pattern: as income per capita increases, CO_2 emissions increase until we reach an income level per capita near to US$18,000. After this income level,

pollution decreases. However, this decline in environmental pressure is not permanent. When the economy reaches a level of income per capita near US$40,000, CO_2 emissions are likely to increase again. In other words, there is a relinking of the environmental pressure-economic growth positive relationship. This suggests a cyclical behavior of pollution and economic growth.
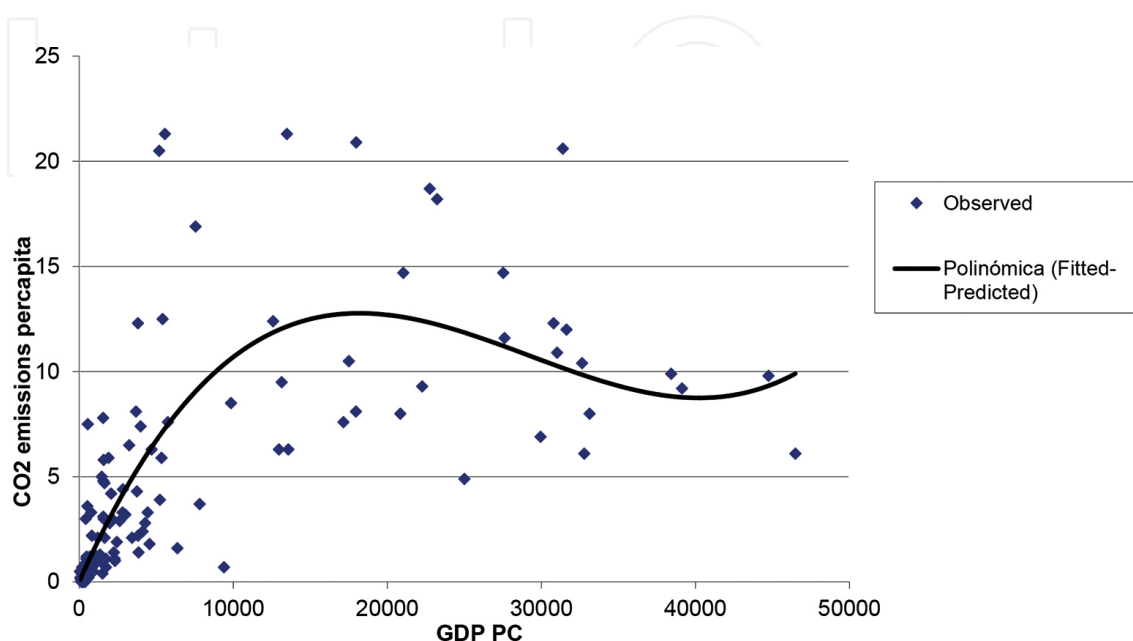

Figure 1. CO_2 emissions and economic growth.

The estimated model is suggestive but not conclusive: the predicted pattern follows an N-shaped curve. The observed behavior of CO_2 per capita emissions suggests that at very low income levels, air pollution occurs at minimum levels. This could be related to low levels of industrial activity. Nevertheless, as per capita income grows, the economy shifts from an agricultural intensive sector to a more industrial intensive sector. This brings as a result more pollution. However, once the economy reaches the turning point of income, air pollution decreases. This decline may be associated with the development of cleaner technologies or a more service-intensive (nonpollutant) sector of the economy. In Ref. [4], the authors discuss other possible explanations for the inverted U-shaped relationship. They argue that at higher income levels, one may observe behavioral changes and changes in preferences that are related to a cleaner environment. For example, individuals are more likely to be willing to pay for environmentally friendly vehicles and ecoproducts. Also, institutional changes may influence the income-pollution relationship; at lower income levels of an economy, institutions that regulate the environment are not very well developed, whereas in rich economies, environmental agencies are more likely to enforce pollution reductions. In fact, the most developed economic instruments designed for air pollution control occur in middle high- or high-income countries.

The next section discusses the theoretical causes that help explain pollution from the point of view of economics. This analysis is highly related to what the first phase of the EKC suggests:

in the absence of pollution control, either from environmental agencies or from economic incentives, higher levels of pollution are likely to occur. Excessive pollution levels cause damages that affect the well-being of individuals who cannot directly control emissions. The question we intend to answer in the next session is, "How can air pollution be explained from an economics' theoretical perspective?" In the subsequent sections, we will discuss the strategies to curve pollution levels.

3. Air pollution as an externality

External effects or *externality* is one of the most basic concepts evoked by economists when looking at problems of environmental pollution (e.g., see [10–12]). In the economics framework, an externality is an important source of market failure that arises when the production or consumption activities of a person or a firm influence the well-being of a bystander. The side effect of the activity on others is typically unintended and uncompensated. A negative externality occurs when the impact of the bystander is adverse and a positive externality when it is beneficial.

Air pollution is essentially a negative externality: it imposes external costs to people who are external to the transaction of a polluting product. Further, economists typically define air pollution as a negative externality in production.

From an economics perspective, demand law suggests an inverse relationship between price and the quantity consumed of a marketable product. However, when a product does not have a very well-established market, this product will be most likely underpriced. This is the case of natural systems such as air or water. The lack of property rights for these natural inputs and the absence of environmental regulation or legal protection to pollution receptors make a firm to perceive air as an input that can be freely used, like a common resource, thus neglecting all external costs imposed to other agents of the economy. In other words, if there were well-defined property rights for air, firms would have to buy the right to pollute it and emissions could be internalized through a market mechanism. When buyers and sellers do not take into account the external costs of their actions while deciding how much to consume or to produce, the market equilibrium is not efficient and the price of a good does not necessarily reflect its social value.

Figure 2 illustrates the previous point through a simple supply and demand analysis. Let us consider the industry of lead smelter. Factories that produce recovered lead ingots from recycled batteries emit pollution. For each ingot produced, certain amount of smoke enters the atmosphere. Because exposure to lead smoke may cause poisoning that affects the central nervous system, especially in children, this smoke is a negative externality. In other words, because there is no market where the external costs that smoke emissions impose to individuals are reflected in the price of lead ingots, this externality affects the efficiency of the market outcome. How?
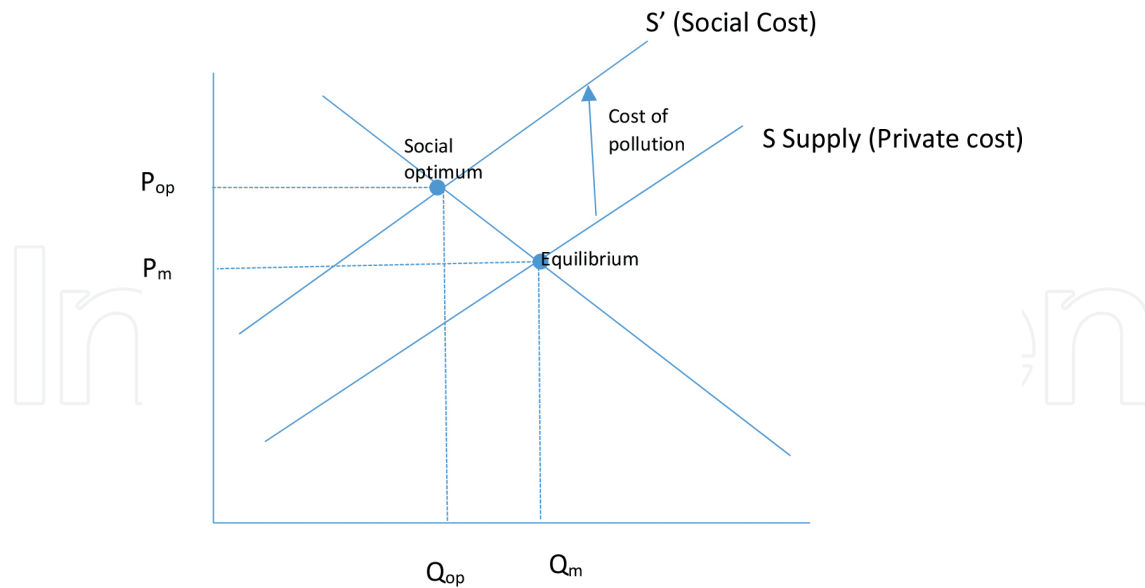
Figure 2. Air pollution externality.

If firms ignore the externality, they decide how much to pollute and will benefit, in the absence of any regulation, from the existence of pollution. With unregulated emissions, firms do not have the incentives to consider the pollution costs to bystanders affected by smokestacks' emissions. Polluters receive the total revenue of pollution; however, the victims of pollution assume all the costs produced by smoke because they cannot control or influence the production decisions of emitters. In this case, the market equilibrium is found where supply equals demand at the equilibrium quantity (Q_m) and the equilibrium price (P_m). In the presence of an externality, however, the cost to society of producing lead ingots is larger than the private costs to the lead producers. The social cost S' includes the private cost plus the cost to the victims of the externality who are affected by pollution. This social cost includes both the private costs of lead producers and the cost to individuals affected by the emissions. If all firms that pollute are forced to pay the full social costs (S') of production that include the external costs of emissions, the competitive supply S (private marginal cost) will shift upward to S' (social cost of pollution) and the externality is internalized. The market price for lead ingots will be higher (P_{op}), and the quantity sold will be lower (Q_{op}). The combination (Q_{op}, P_{op}) is a social optimum, because it denotes the desirable amount of lead ingots produced from the stand point of society as a whole. This graph reveals that, at the social optimum, reductions in pollution are accompanied by reductions in the supply of the product that contributes to emissions.[2]

In Section 4, we discuss some public policies proposed to achieve the optimal outcome where the externality is internalized as well as private solutions for the treatment of externalities. For this purpose, we focus on environmental quality as a problem of the commons.

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[2] S, the supply curve, is the marginal cost for the firm that maximizes profits. At the optimum, price = marginal cost for a competitive firm. S' is the marginal social cost of production, which in turn equals the marginal cost of production plus the marginal external cost of emissions.

4. Environmental policies to correct air pollution externalities

Environmental quality shaped by air pollution entails a critical commons problem. Economists have long discussed that externalities arise when resources are treated as commons that are shared by many users without payment. In the absence of rationing, the presence of free-access common property resources may lead to the overutilization of the resource thus creating market inefficiencies [13]. The atmosphere has the characteristics of a common property resource. Economic theory that focuses on market failures arising from incomplete systems of property rights defines clean air in the atmosphere as a particular form of commons problem: pure public goods that are nonexcludable and nonrival in consumption (see [14]). This type of public goods provides benefits to people or firms at zero marginal costs and does not exclude someone from enjoying them. The presence of such pure public goods has triggered governments to design environmental policies. Some of these policies follow a command and control approach that does not account for economic responses. Often, economists argue that these policies are not cost-effective, sometimes bring unintended consequences on the environment, and sometimes are ineffective. This approach has essentially used legislation to correct pollution externalities through uniform standards. Other environmental policies have emerged taking into account economic incentives, making pollution an expensive activity in the form of pollution taxes and marketable permit system. We will briefly discuss these approaches in the following session.

4.1. Standards

A standard is a legal form of regulation that limits how much pollutants a firm can emit. Under this approach, the government usually implements the so-called command and control policies to regulate polluting activities. In other words, the environmental authorities regulate behavior directly by dictating a maximum level of pollution that a factory may emit (safety standard), or by requiring firms to impose the adoption of abatement technologies for reducing emissions (technology standard).

4.1.1. Safety standard

Early regulation of air pollution was based mainly on the so-called safety or ambient standard. Safety standard can be simply defined as a maximum level for some pollutant in the ambient environment. Safety standards are usually expressed as average concentration levels over some period of time. In the US, the Clean Air Act, last amended in 1990, requires the US Environmental Protection Agency (EPA) to set National Air Quality Standards (NAQS) for the so-called criteria pollutants: particle pollution, photochemical oxidants and ground-level ozone, carbon monoxide, sulfur oxides, nitrogen oxides, and lead. For example, the US standard for particulate matter less than 10 $\mu g/m^3$ (PM10) requires that a 24 h average of 150 $\mu g/m^3$ not be exceeded more than once per year on average over a 3-year period.[3] Safety

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[3] A table summarizing NAQS is reported by the US Environmental Protection Agency at https://www.epa.gov/criteria-air-pollutants/naaqs-table#4.

standards are essentially stock levels of pollution that are set to protect the health of people or their well-being. The safety standard approach was conceived in terms of rights and fairness rather than efficiency. The vision of the safety standard requires pollution reductions to minimum levels to eventually eliminate damage to the environment and risks to people's health. This approach is based on legislation that seldom mentions cost-benefit tests. Advocates of this approach usually argue that in the case of environmental protection, costs should not be involved in people's decision-making processes. Safety standards, however, usually are accompanied by high compliance costs and are subject to several criticisms: first, they are considered inefficient in the sense that regulators may have chosen pollution levels that are too high compared to standards based on costs and benefits. Second, safety standards are not necessarily cost-effective. In other words, not always the maximum amount of safety is achieved with the available resources. The final criticism to safety standards is that pollution control may have a regressive impact on income distribution. This means that higher prices of goods consumed triggered by environmental regulation affect a greater proportion of the incomes of poor households than those of richer households [15]. A comprehensive discussion of the potential regressive impacts of pollution control measures is reported in Ref. [16].

4.1.2. Emission standard

An emission standard is a flow variable and may be defined as the maximum level applied to the quantities of emissions coming from a pollution source. Sometimes this standard is known as a performance standard because it is an end result of compliance that the environmental authority requires from final pollution sources. In this case, the authority regulates quantities. In the case of air pollution, a standard may be expressed as a quantity of material per unit of time, per unit of output, or per unit of input. For example, an emission standard may be set as SO_2 emissions per kilowatt-hour of electricity produced, or sulfur content of coal used in power generation. A common emission standard is the mobile source air pollution program where EPA establishes emission standards for new cars by mandating ceilings on emissions per mile of operation.[4] It is worth noting that the compliance of emission standards does not mean that ambient standards are met. Complex chemical processes may change the physical properties of the pollutant, and the environmental authorities usually do not have control over the numbers of cars circulating, making it difficult to control the ambient air quality.

From a theoretical economic point of view, emission standards are set taking into account what economists define as efficient pollution levels. An efficient pollution level may be defined as the one that maximizes the net benefits of reduction. This level occurs theoretically where the marginal costs of pollution reduction equals its marginal benefits. Efficient levels are illustrated in **Figure 3a, b** where total costs and benefits of pollution reduction (**Figure 3a**) and marginal costs and benefits of reduction are shown. Starting from an initial and not efficient level of emissions e_1, the efficient level occurs at e^* where net benefits are maximum. At this point, the slope of the total benefits function (marginal benefit) equals the slope of the total cost function (marginal cost). The point e^* is illustrated in **Figure 3b**. The pollution level where total costs of

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[4] Details found in the Clean Air Act Mobile Source Fuels Civil Penalty Policy Title II of the Clean Air Act 40 C.F.R. Part 80 Fuels Standards Requirements.

reduction equal total benefits of reduction would lead to too much control of pollution from an efficiency point of view. In practice, the environmental authority sets a standard to the theoretical level e^* and enforces the standard by measuring pollution at the source and putting fines to firms in case detecting possible violations.
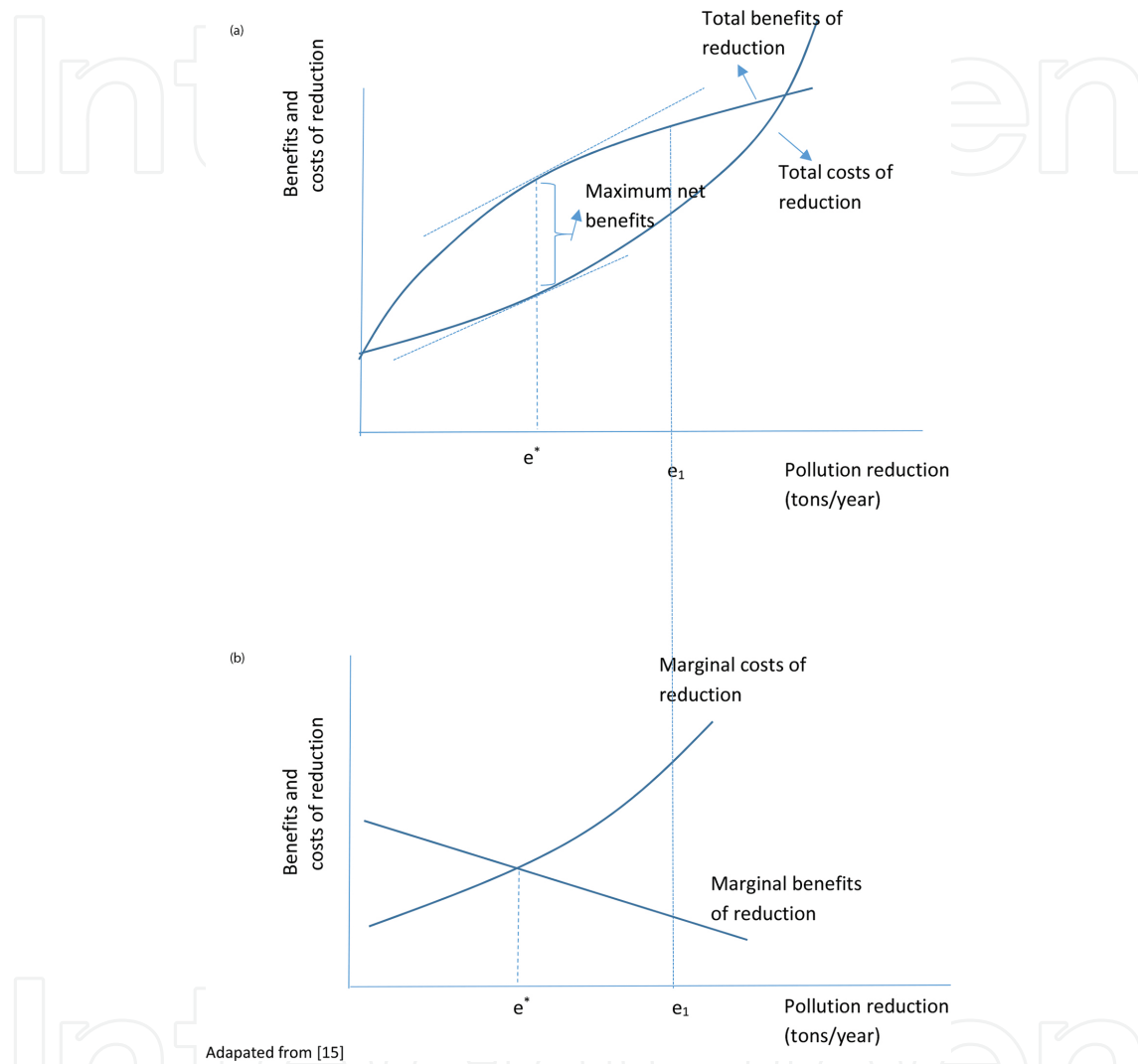

Adapted from [15]

Figure 3. (a, b) Emission standard.

Under the scheme of emission standards, firms have the flexibility to choose the pollution abatement method to meet the standard. Other forms of regulation focus on the practices and technology adoption that emitters must adopt to meet the mandated goal of emission levels. We will briefly discuss technology standards below.

4.1.3. Technology standards

An environmental agency may specify a particular type of technology that a polluter must adopt in the production process. Also it may specify the characteristics of the inputs that must

be used in production or the pollution abatement technologies such as stack gas scrubbers to directly reduce emissions. Overall, this regulatory approach receives the name of *best available technology*. The technology prescribed usually meets two conditions: it must achieve significant reductions in pollution, but at a reasonable cost (see [12]).

The standards described above in this section are labeled as quantity or direct regulation. Under this regulatory view, policy makers control pollution through legal regulations by specifying emissions ceilings or the technology to be used in production or abatement. Under the regime of standards, the regulator (government) is responsible for how much pollution is allowed to each firm, mandating a specific technology, and, most importantly, for the monitoring of emissions to verify compliance and the implementation of monetary penalties to noncomplying sources [17]. Economists have claimed that the standards regime is not cost-effective (it does not achieve the emission target at a minimum cost), and have proposed a regulatory approach based on economic incentives. The idea behind incentive-based regulation was to make polluting an expensive activity and lower the costs of pollution control by letting the pollution abatement decisions to firms and not to the regulator [15]. The following section briefly discusses the major regulatory schemes based on incentives, namely the pollution tax and the marketable permit system.

4.2. Incentive-based regulation for air pollution control

Two historical economic views of environmental problems have shaped the incentive-based regulation for pollution control. The first view follows the tradition of Pigou [18] who thought on environmental pollution as a negative externality problem. In the presence of an externality such as air pollution, Pigou argued that imposing a per unit tax on the emissions firms would internalize the externality. The tax rate would be equal to the marginal social damage caused by the last unit of pollution at the efficient allocation [17]. The second economic view to tackle environmental problems follows the tradition of Ronald Coase [19] who thought of environmental pollution as a problem of public good. Coase demonstrated that in the absence of transaction costs and free riding, it is possible to achieve an efficient pollution level through negotiation regardless of who has the legal right to pollute or prevent pollution [19]. This theorem is usually evoked when analyzing the initial distribution of permits in a marketable permit system, a trading market in pollution rights.

4.2.1. Emission taxes

One of the main criticisms of command and control as a regulatory approach is that standards hinder the cost-effectiveness of pollution control since they allow little flexibility in the means of achieving lower pollution levels. The cost-effectiveness rule says that cost-effectiveness is achieved if all sources that control pollution experience the same marginal cost of reduction [10]. In the standards approaches to regulate the environment, firms are forced to take similar shares of the pollution control burden by imposing uniform standards in both performance and technology. In practice, abatement costs are very heterogeneous among firms placing command and control methods as not cost-effective. The regulator could employ nonuniform standards to each source in order to achieve cost-effectiveness; however, the information

burden that the regulator would have to carry, in order to know each source's abatement costs, is in practice unfeasible or very expensive [14]. Theoretically, a Pigouvian tax is a way by which the government can achieve the pollution reduction goal by giving factory owners an economic incentive to reduce pollution. Since a Pigouvian tax places a price to the right to pollute, the higher the tax, the larger the reduction. The environmental authority can achieve the desired level of pollution by setting an emission tax at the appropriate level. Theoretically, this tax is fixed at the efficient pollution level where the marginal damage of emissions equals the marginal abatement costs [20]. This tax is shown in **Figure 4**.[5]
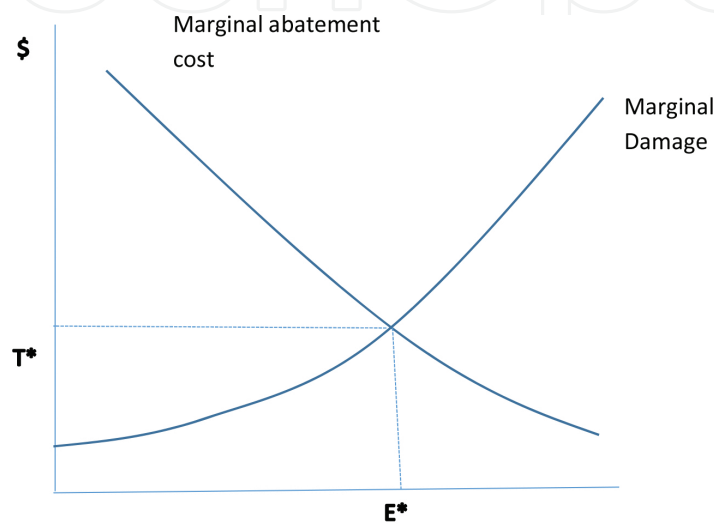
Adapted from [20]

Figure 4. Emission tax.

One of the main advantages of emission taxes is their economic efficiency. When the marginal cost of pollution reduction at one factory is greater than that at another factory, the overall costs can be reduced without changing the ambient pollution level by decreasing pollution at the low-cost site and increasing it at the highest cost site [15]. In other words, the emissions tax leads firms with lower marginal abatement cost to larger reductions compared to those from firms with larger marginal abatement costs. Each firm would reduce its emissions until its marginal reduction costs equal the tax; then, marginal abatement costs will be the same for all sources and the cost-effectiveness rule holds.

The previous point is illustrated in **Figure 5**. Firm A has lower marginal abatement costs than firm B. This difference may be attributed in practice to differences in production technologies. The production technology used by firm A makes reductions less costly than reductions at firm B.

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[5] The main difference between graph 3 and 4 is that graph 3 is in terms of pollution reductions and graph 4 is in terms of emissions.
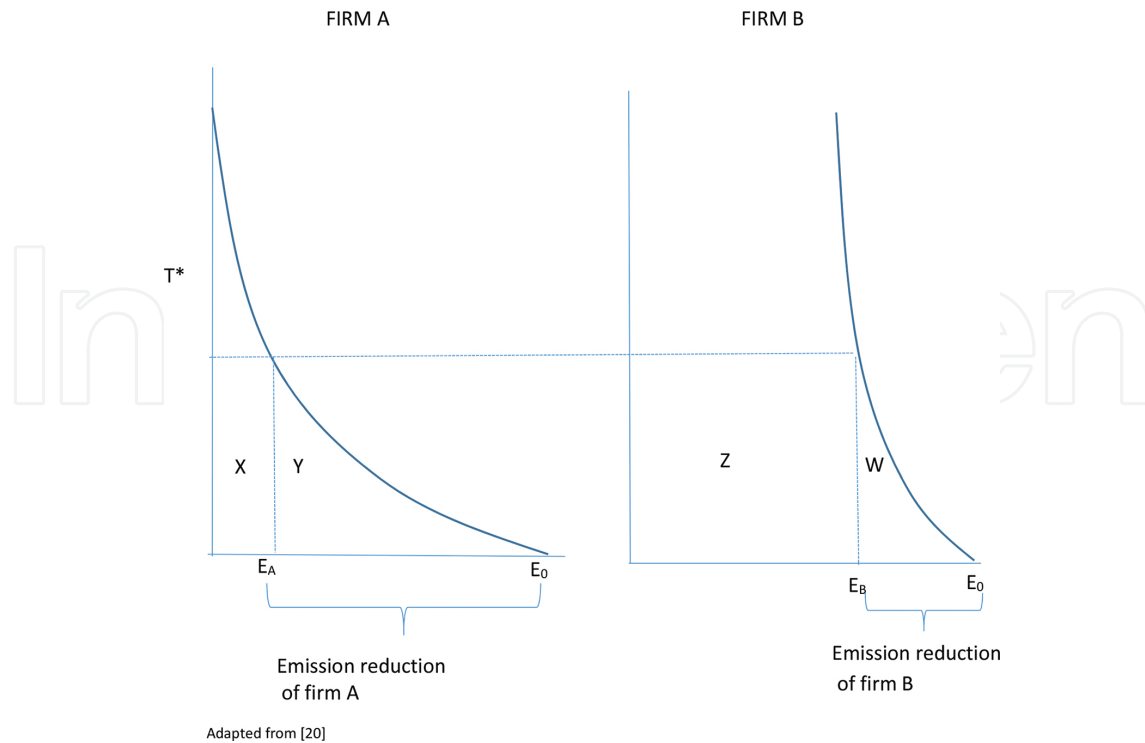
Adapted from [20]

Figure 5. Emissions reductions and abatement costs.

The emission tax leads firm A to reduce from E_0 (initial level of emissions) to E_A, while firm B would reduce a lower quantity, from E_0 to E_B. In other words, because of the tax, the firm with lower marginal abatement costs would have a larger proportion of the emissions reductions. Note that total abatement cost for firm A equals area Y and for firm B it equals area W. The tax bill that would be sent to firm A equals area X, whereas for firm B the tax bill is much larger and equal to area Z. One of the main advantages of emission taxes is that the regulator does not need to know information on abatement costs to reach efficient levels of emissions. Economists, in general, prefer the tax to standards because the tax reduces pollution more efficiently. In our example, firm A, which has lower marginal costs of abatement, responds to the tax by reducing emissions substantially to avoid the tax. Firm B, for which it is more expensive to reduce emissions, responds to the tax just by reducing less and paying the tax. The emission tax approach differs from standards where, notwithstanding the marginal reduction costs for each firm, all firms have to reduce the same amount, thus making uniform standards non-cost-effective.

4.2.2. Tradable emissions rights

Following the tradition of Ronal Coase [19], who proposed to view harmful effects such as smoke or noise as rights, economists used his key insight to propose a price-based remedy for pollution control, based on a system of transferable or tradable emission permits. A detailed review of this regulatory approach is found in Refs. [20–22]. The basic idea of the system of marketable permits for emissions is that each firm must have permits to generate emissions. Each permit specifies the quantity of emissions allowed to the firms. For example, each permit

represents one unit of emissions. If firms do not comply with the specified emissions, they would be subject to strong sanctions. Emission permits are allocated among firms. The initial allocation is a centralized decision, the total number of permits is less than the current amount of emissions, and some or all sources would receive fewer permits than the current amount of emissions. The total number of permits is chosen to achieve a level of emissions to guarantee the desired ambient quality. The permits are marketable; that is, they can be bought and sold by any firm participating in the market. The idea behind this approach is that firms that can reduce pollution more easily, because of facing lower marginal abatement costs, would be willing to sell permits, and firms that face high costs of reduction would be willing to buy whatever amount of permits they need. The free market for pollution rights is also seen by economists as an efficient way to achieve optimal pollution levels for society. In the design of marketable emissions programs, economists create a market for pollution externalities. This approach combines some of the advantages of standards with the cost-effectiveness of the Pigouvian tax: the agency administering the program determines the total number of permits (like in a standard approach) and the transferability of permits allows cost-effective pollution abatement like in the tax system.

The US has a long tradition of tradable emission programs. These programs have also become more popular around the world. Early attempts by the US EPA to implement tradable emissions rights include the offset policy. Under this program, new sources of emissions may be located in regions where pollution standards were not met ("nonattainment" regions) as long as they offset their new emissions from existing sources by reducing their emissions below their current legal requirements. EPA would certify these reductions as emission reduction credits. These credits created a supply that became transferable to new sources interested in entering the area (demand). One of the advantages of the offset policy is that it helped improve air quality without impeding economic growth. The early offset program expanded to the US Emissions Trading Program which established three trading programs: offset, bubble, and netting policies. The offset policy worked as explained before. The netting policy allowed existing sources to expand, avoiding technological requirements for pollution control as long as any net increase in emissions fell below an established limit. The bubble policy diverges from the offset policy because emission reduction credits could be traded among existing sources in localized air quality regions ("bubbles"), whereas in the offset policy *new* sources are allowed to acquire credits from existing sources.

Tradable emission rights have been applied in the US to control inputs such as lead in gasoline [23], to reduce ozone-depleting chemicals mandated by the Montreal Protocol, to tackle acid rain through the Sulfur Allowance Program, to reduce NO_x with the NO_x Budget Program, and to reduce volatile organic matter (VOM) emissions with the Emissions Reduction Market System (ERMS) in the Chicago area [17]. One of the most important emission trading programs is California's Regional Clean Air Incentives Market (RECLAIM) to control nitrogen oxides and sulfur in a market with more than 400 industrial polluters participating [21]. Non-US experience includes the European Union Emissions Trading Scheme to reduce industrial greenhouse emissions. Emissions trading programs have also been implemented to control particulate matter in Santiago de Chile [24].

5. Cost and benefits of air pollution control

The economic analysis of cost and benefits of air pollution control entails two main complexities: first, the taxonomy of the costs of environmental regulation is extensive and evaluated from different points of view, And second, many of the benefits of air pollution control and better ambient quality are nonmarketable, and, therefore, they cannot be easily monetized. For many policy makers, the costs of environmental regulations are mainly defined by the cost to government of administering environmental laws and regulations. These administrative costs are mainly from monitoring and enforcement. On the other hand, from the point of view of private firms there are costs of compliance given by the capital and operating expenditures to meet emission standards. Part of the compliance costs may be shared also by the regulator, for example, when clean technologies are subsidized. Other "negative costs" or nonenvironmental benefits linked to environmental regulation include productivity impacts of a cleaner environment or innovation stimulation. Other costs encompass the discouragement of investment, for example, when a firm closes because it cannot afford expensive pollution abatement technologies, retarded innovation, and other economic impacts including the loss of jobs. Jaffe et al. report in Ref. [25] that the direct compliance costs for the private sector in the US represent nearly 2.6 of gross national product (close to US$125 billion). The biggest share of these compliance costs is business pollution abatement expenditures (61%). Other components of these costs included personal consumption abatement (11%), government abatement (23%), government regulation and monitoring (2%), and research and development (3%).

Indirect benefits from air pollution control also include those that are nonmarketable. Acid rain and exposure to particulate matter can affect human health and are usually linked to increased risks of lung disorders such as asthma and bronquitis. They also have been linked to premature mortality in adults and children. Acid rain or particulate matter may cause damages in ecosystems, including water bodies and forests, and may also damage human-made infrastructure [26]. Bazhaf et al. estimated 1980s benefits from reducing sulfur dioxide in a 50% in the Adirondacks region in the US. The authors found annual benefits of US$24 million from improvements in recreational fishing, US$700 million to grain crop producers, and US$800 annual value for the commercial timber sector [27]. Other efforts to measure benefits of air quality improvements include the monetary estimation of the impacts of air pollution in human health. The World Bank estimated that mortality and morbidity from urban air pollution in India and China meant annual losses that varied between 2 and 3% of GDP [28]. More recently, Cropper and Khanna evaluate the methods used by the World Bank to calculate economic costs related to the exposure of outdoor air pollution [29]. They recommend the usage of estimates of disability-adjusted life years (DALYs) lost due to outdoor air pollution produced by the Global Burden of Disease model (GBD) to calculate the monetary value of a statistical life. Other economic literature on nonmarket valuation has estimated the impacts of air pollution on property values. These studies use direct methods of environmental valuation, using as a framework Rosen's hedonic pricing model [30]. The basic idea of this analytical framework is to learn about the price of air quality (a nonmarketable good) by observing the housing market. The main assumption is that housing is a marketable good composed by a bundle of heterogeneous characteristics that do not have a market, including air quality of the

neighborhood where the house is located. By observing the housing market, we can indirectly observe trade-offs that individuals are willing to make with respect to a characteristic. A consumer of housing will be willing to pay more for a house located in a clean air environment than for an identical house in a polluted area, *ceteris paribus*. This differential in price is an approximation of the willingness to pay or implicit price of air quality. A long tradition of hedonic models examining the impact of air pollution on property values has been in the nonmarket valuation literature. These estimations are important efforts that economists have done to find a monetary value for air quality. Applications of the hedonic model relating property values with air pollution include [31–36]. More recent applications include but are not limited to Refs. [37–42]. All of these studies estimated the so-called hedonic price function that relates property values to air pollution levels and other characteristics of the structure of dwellings (e.g., area, bathrooms, number of rooms) and other local environmental amenities such as proximity to parks, proximity to main roads, proximity to noxious facilities, among others. Results from the valuation exercises are very contextual and differ from one city/country to another. For example, in Ref. [36] researchers found that in the US a unit ($\mu g/m^3$) reduction in total suspended particles increases mean housing values between 0.2 and 0.4%. In other application of the hedonic model, the authors found that marginal implicit prices for PM10 air pollution in Santiago de Chile ranged from US$3 to US$6 depending on the estimation method [40]. In Bogotá, Colombia, the marginal implicit price for pollution measured as the annual average PM10 levels varied from US$ 0.31 in lower income neighborhoods to US$4.58 in higher income neighborhoods, also depending on the estimation method [42]. All hedonic valuations estimating the impact of pollution on property values suggest that air pollution improvements capitalize into housing values. These results from hedonic model estimations are important for policy makers related to air pollution control because benefits from housing capitalizations could be considered in cost-benefit analysis of pollution abatement.

6. Discussion

The debate on economic growth and the environment is not a closed one among economists [43]. The relationship between economic growth and pollution is suggestive if we accept the environmental Kuznets curve. In this chapter, we illustrated the nature of the EKC and the possible explanations for the inverse U relationship between economic growth and pollution. One of the most echoed explanations for the inverse U relationship is the impact of regulation on pollution abatement [5].

Usually, pollution is perceived as an economic problem associated with production and consumption; however, it is important to recognize the public good properties of the environment that may cause pollution. Pollution could be explained, from an economic point of view, as a by-product of a market failure. The environment is perceived by polluters as a public good that is a nonrival and a nonexclusive good for which property rights are not well defined. This kind of market failure makes firms perceive polluting activities as costless; however, this chapter has shown that there are external costs of air pollution. If the objective of an environmental authority is to reduce pollution, we have discussed the basic nature of instruments that

the regulator may use for pollution control, emphasizing on standards and economic-incentive-based regulation: namely the Pigouvian tax and Emissions Trading. This chapter highlighted the advantages of incentive-based regulation compared to the command and control approach for pollution abatement, as it is frequently discussed within the economics discipline.

However, environmental regulation is not limited to standards or to the incentive-based regulation pointed out in this chapter. Other approaches to environmental regulation include decentralized policies where coordination among polluters is facilitated because of small numbers involved. Within these approaches, there are liability laws, well-defined property rights, and moral suasion (Field, 1994). Other environmental policies initiatives that have been used recently in developing countries rely on information and public disclosure as an initiative for industrial pollution abatement. An emblematic program using this approach is the Program for Pollution Control, Evaluation, and Rating (PROPER), launched in Indonesia [44]. As economists recognize the potential trade-offs between clean air and economic growth, and the impossibility of a zero pollution environment, economics as a discipline has proposed incentive-based regulation as a cost-effective way to control air pollution. The application of incentive-based regulation is compatible with the Intended National Determined Contributions (INDCs) agreed upon in the United Nations' Framework Convention on Climate Change (UNFCCC) Conference of the Parties (COP21) in Paris in December 2015, to tackle global climate change. As this chapter suggests, economics as a discipline complements the efforts of governments and engineers to reduce industrial pollution.

Appendix

Group of countries	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
High income	17.9	17.0	16.6	16.4	16.3	16.1	16.1	15.9	15.4	14.4	15.0	14.9	14.8	14.9
Upper middle income	24.7	24.5	23.3	24.1	24.1	23.9	23.9	23.9	23.7	23.0	23.2	21.6	21.2	20.8
Middle income	22.8	22.6	21.9	22.6	22.6	22.5	22.5	22.4	22.2	21.5	21.6	20.5	20.2	19.8
Lower middle income	17.1	17.2	17.3	17.3	17.5	17.4	17.5	17.4	17.2	16.6	15.9	16.8	16.6	16.3
Low income	10.2	11.2	11.5	11.3	11.0	10.5	10.4	10.4	10.2	9.9	9.0	9.1	8.8	8.6
World	19.2	18.5	18.1	18.2	18.2	18.0	18.0	17.8	17.3	16.4	16.8	16.5	16.3	16.3

Source: World Development Indicators.

Table A1. Manufacturing, value added (% of GDP).

Group of countries	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
High income	14	14	13	13	13	12	13	12	12	12	12	13	12	12
Upper middle income	23	22	22	22	24	25	24	24	25	25	25	26	25	25
Middle income	23	22	22	22	23	24	24	24	24	24	24	26	25	25
Lower middle income	21	21	21	22	21	22	23	23	23	22	23	23	22	22
Low income	48	48	47	48	47	47	48	45	46	45	44	39	38	37
World	18	18	17	17	18	18	18	18	19	19	19	20	20	20

Source: World Development Indicators.

Table A2. CO_2 emissions from manufacturing industries and construction (% of total fuel consumption).

Variable name	Definition	Mean	SD	Min	Max
Y	2000 year GDP at market prices, constant 1995 US$ (WB estimates)	6468.67	10518.07	45.605	46485.31
CO_2	Carbon dioxide emissions (CO_2), metric tons of CO_2 per capita (Year 2000)	4.303521	5.33227	0	21.3

CO_2 per capita emissions used for Eq. (2) comes from United Nations data base. GDP from 2003 World Development Indicators by the World Bank (WB).

One hundred and fifty-two countries are included in the sample. The 2000 per capita GDP variable is measured at market prices in constant 1995 US$ (WB estimates). According to the United Nations Definition, the variable CO_2 measures emissions in metric tons of CO_2 per capita. Emissions of CO_2 refer to the release of greenhouse gases and/or precursors into the atmosphere over a specified area and a period of time. In our case, the time period for emissions is year 2000 and each area corresponds to each country in the 152 observations sample.

Table A3. Descriptive statistics.

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