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# Are renewable quotas effective to reduce CO2 emissions?

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# Are renewable quotas effective to reduce $CO_2$ emissions?[*]

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**Abstract**

We quantify the intertemporal impact of a renewable quota on CO2 emissions, pollution and welfare. We find that a quota substitutes investments in baseload technologies. Therefore quotas have little impact on CO2 and pollution in systems that expand baseload with hydro. We also find that quotas can be quite expensive and their impact is highly nonlinear. With detailed data on Chile's system we estimate that a 5% quota is not binding, a 10% quota causes a small deadweight loss but a 20% quota multiplies the deadweight loss by a factor of 55, to about 7% of the system's supply cost.

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# 1 Introduction

It is often thought that imposing quotas that force investments in nonconventional renewable energy are effective to reduce pollution and $CO_2$ emissions.[1,2] Still, there is little research that assesses the effectiveness of quotas and evaluate their costs. How effective are renewable quotas to reduce $CO_2$ emissions and pollution? And how expensive are they? We show that unless fossil fuel technologies are part of the base load, quotas are ineffective and, in any case, very expensive.

To quantify the intertemporal impact of renewable quotas on $CO_2$ emissions, pollution and welfare and model investment decisions we use our integrated assessment model Emma (Spanish acronym for "electricity, markets and the environment"), using Chile's Central Interconnected System (CIS) as a case study. Emma overcomes two shortcomings of standard cost-benefit analysis of environmental policies in the electricity industry. First, it jointly solves for the private investment plan in capacity and the operation of the system. This is important because, as we explain below, most of the effects of environmental policies work through endogenous adjustments of the investment plan. Second, most standard cost-benefit assessment models assume that demand does not respond to price changes. This omission is unfortunate because it obscures the fact that environmental policies directly affect consumption growth and consumer surplus and, we show, these effects are large.

Our main finding is that a renewable quota substitutes mainly investments in base load technologies and barely touches the rest. Therefore, the environmental benefit of a renewable quota depends mainly on the emission intensity factors of the base load technologies that the quota substitutes, not on system average emission intensity factors. Because in many systems hydro is the technology that expands with base load demand, renewable quotas may have little if any impact on emissions.[3] Indeed, we show that renewable quotas will have almost no impact in Chile's CIS for the next 20 years, because they substitute investments in hydro. Only when profitable hydro resources are fully used many years from now, the quotas will substitute investments in coal, and have sizable effects on lowering emissions.

Our second finding is that renewable quotas are quite expensive and their impact is highly nonlinear. In the case of Chile's CIS a 5% quota is not binding, a 10% quota causes a small deadweight loss, but increasing the quota from 10% to 20% multiplies the deadweight loss by a factor of 55. A renewable quota also has

[1] Nonconventional renewable energy sources include geothermal, wind, solar, tidal, biomass, landfill gas and small hydroelectric power plants. Hydro projects smaller than 20MW and a fraction of hydro plants between 20MW and 40MW are considered nonconventional renewable energy in Chile.

[2] Quotas are one of many policies that countries have used to promote renewables and counter the fact that they are seldom privately profitable. Among other policies are auctions, feed-in tariffs, fiscal incentives, like tax credits. So far, 118 countries have mechanisms to support renewable energy and at least 96 countries have set electricity generation targets with renewable energy. See Renewable Energy Policy Network for the 21st Century (2011).

[3] It has been argued that reservoirs are net producers of $CO_2$ because they generate methane ($CH_4$). Nevertheless, Svensson (2005) performed a study of 167 hydro power stations which exhibits that reservoirs emit 75g$CO_2$/kWh on average and a median of 6.7g$CO_2$/kWh (the methane emissions are shown in its $CO_2$ equivalent), assuming their "extreme estimate" of methane emissions. Note that the average value and the median are, approximately, 1/4 and 1/50 of the $CO_2$ intensity factor of a combined cycle gas fired plant (which is above 300g/kWh).

Also, if a reservoir is very intensive in methane generation, like large tropical reservoirs built over densely forested areas, Ramos et al. (2009) exhibit that it is possible to extract and pump the methane at a lower cost than the market price of natural gas, then, reducing substantially the $CO_2$ intensity factor of those reservoirs.

important redistributive effects, which are also highly nonlinear. A quota rises the price paid by consumers. With a 10% quota, they lose the equivalent to 3% of the system's cost. But with a 20% quota the loss rises by a factor of 5, to the equivalent of about 16% of the systems cost of supply.

With the opposite sign, the same happens with producers' gains. Because the supply curve of renewable energy is upward sloping and steep, Ricardian rents are substantial. Indeed, with a 10% quota the owners of renewables earn a Ricardian rent which is equivalent to about 3% of the system's cost of supply. With a 20% quota, Ricardian rents increase about four times to about 12% of the system's supply cost.

We contribute to a growing literature on the economic and environmental effects of renewable quotas. Bushnell (2010) and Chao (2011) find that increasing investments in intermittent renewable energy (e.g. wind) decreases the optimal capacity of base load technologies (hydro, coal, nuclear or combined-cycle gas plants as the case may be) and increases the optimal capacity of peak load technologies (combustion turbines). We complement this analysis by quantifying the environmental and economic impact of renewables in a long term horizon, considering the dynamic effects as demand for electricity grows and renewables deplete.

The rest of the paper is organized as follows. Section 2 discusses three preliminaries: it presents the renewables' supply curve, explains the basic economics of a quota and discusses how to measure the damage wrought by pollution. Section 3 presents our analysis of quotas. Section 4 concludes.

# 2 Preliminaries

## 2.1 Availability and levelized costs of renewable energy in the CIS

The Central Interconnected System (CIS) extends from Chile's II region to its X, covering around 92.2% of Chile's population, and comprising around 76% of its total installed capacity. In December 2010 CIS total capacity was 12,147 MW. On average, about two thirds of the energy generated comes from hydro plants. Hydro generation is complemented with natural gas-fired turbines (22.2% of installed capacity[4]), coal (11%), diesel turbines (16.2%) and renewable energy (4.3%).

How much renewable energy is available in the CIS? Table 1 and Figure 1 present the first estimate of the supply curve of renewable energy in Chile's CIS. We estimate that the total availability of renewable energy is approximately 9,280 MW that can produce 50,700 GWh/year on average.[5] This might seem sizable given CIS's current installed capacity, but the last row in Table 1 shows that the levelized cost of energy varies and in most cases is much higher than the levelized cost of conventional base load technologies, like large hydro projects or coal (coal's levelized cost of energy is approximately US$80/MWh in Chile). Thus, a sharp distinction must be made between physical and economic availability of renewable energy. Indeed, as can be seen from Figure 1, there are barely 2,500 GWh/year available at levelized cost of less than US$80/MWh,

[4]Due to Argentine's natural gas restrictions, currently only 6% of the CIS capacity is running with natural gas, while the rest of the natural gas fired turbines are running with diesel. These plants will run again with natural gas as imports of LNG increase within the next 10 years.

[5]Of course, the availability of generation with renewable energies in a year depends on the local climate conditions, especially for small hydro, wind and solar.

which is the market price of electricity, $p^m$. Any expansion of renewables beyond that requires subsidies. The area $A$ are the Ricardian rents earned by those projects.

Figure 1 also shows that the supply curve of renewable energy is upward sloping and that the slope varies significantly, being very steep in some sections. This might seem obvious and hardly worth mentioning, but for the fact that most of the time analysts assume a uniform levelized cost for each technology, a very misleading assumption. For example, the levelized cost of energy of small hydroelectric plants, in Table 1, varies from US$70/MWh to US$186/MWh as a consequence of the volatility of the river flow, hydraulic head and location, because resources are located at different distances from the transmission system. Similarly, the levelized cost of a wind farm varies from US$137/MWh to US$202/MWh, depending on the capacity factor. And the levelized cost of geothermal projects varies from US$121/MWh to US$180/MWh with the probability of finding an appropriate source. As said, most of current evaluations of policies that foster investments in renewable energy ignore heterogeneity. Instead, they assume a marginal technology with unlimited availability and constant levelized cost, or, when considering limited availability of resources, costs are assumed constant within technologies.

## 2.2 The basic economics of a quota

As we have already said, if renewable energies are fostered through a quota set lower than 2,500 GWh/year, the policy is unnecessary. But if the quota exceeds 2,500 GWh/year, the policy encourages additional investments on renewable energy. The basic economics is as follows.

Assume, for example, that the policy creates a demand for $q^r$ = 20,000 GWh/year. The marginal project will establish the price $p^r$ that will be paid for each GWh generated with renewable energy. In Figure 1 we see it is approximately US$165/MWh. Therefore, the total subsidy that consumers will pay is the area $B + C$, that corresponds to

$$(p^r - p^m) \times q^r \tag{1}$$

Not all the subsidy corresponds to a deadweight loss, only the area $C$ does. The rest of it, area $B$, is a transfer from consumers to the owners of renewable projects—a Ricardian rent. The renewable quota will increase the Ricardian rents of these producers from area $A$ to area $A + B$.

Note that generation targets with renewable energy are usually set relative to the system's total generation or consumption. Therefore, as the demand for electricity grows over time so will the demand for renewable energy, the price $p^r$ paid to renewable projects, and the overall cost of the renewable quota. Also, because the supply curve of renewable energy is upward sloping, the cost of the quota is highly nonlinear with its size. Last, the cost of a renewable quota will vary across countries, because it depends on the local costs and availability of renewables.

Note that support mechanisms for investments in renewable energy, implemented through quotas or auctions, are equivalent to foster renewable energy through prices. The price $p^r$ that receive producers of renewable energy can be set through feed-in tariffs and fiscal incentives, achieving the same generation $q^r$. Therefore, ceteris paribus, the costs of these mechanisms should be similar.[6]

[6] In practice, the cost of mechanisms that foster renewable energies through prices varies because they achieve unexpected

## 2.3 The damage wrought by $CO_2$ and air pollutants

Power plants that run on fossil fuels emit $CO_2$ and other greenhouse gases (GHGs), and air pollutants: particulate matter ($PM_{10}$ and $PM_{2.5}$), sulfur oxides ($SO_x$) and nitrogen oxides ($NO_x$). $CO_2$ emissions contribute to global climate change. The damage they cause does not depend on where the emission occurs. On the other hand, air pollutants affect only the area surrounding the source, damaging health, materials, visibility and crops.

**The damage caused by air pollutants** We quantify the total damage caused by the emission of an air pollutant through the marginal damage caused by its emissions. The marginal damage of the emission of an air pollutant is the value assigned to the externality wrought by emitting one additional ton of the air pollutant.

Formally, if $md_i(s)$ is the marginal damage of the air pollutant $i$ when the amount emitted is $s$, then the total damage ($D_i$) caused by the emissions $t_i$ is

$$D_i(t_i) = \int_0^{t_i} md_i(s)\, ds \tag{2}$$

We assume that the marginal damage is constant within a locality, no matter the amount emitted by each power plant. Therefore, the total damage of emissions of a power plant is linear with the amount emitted. Hence (2) can be simplified to

$$D_i(t_i) = md_i \times t_i \tag{3}$$

It is important to distinguish between marginal damage and marginal per capita damage. Per capita damage is the harm on a particular individual or thing (e.g. a building) by a given concentration level of a given pollutant. The marginal damage wrought by an additional ton of the pollutant, on the other hand, is a linear function of the number of individuals and marginal per capita damage, vis

$$md_i = (\#\text{ of individuals}) \times (\text{damage per person})_i \tag{4}$$

A straightforward implication of (4) is that marginal damages grow with the size of the population around the source, ceteris paribus.

Table 2 exhibits the estimates of the marginal damages caused by $PM_{2.5}$, $NO_x$ and $SO_x$ in Chile and the United States. For Chile, we use the estimates of Cifuentes et al. (2010) for the marginal damages of $PM_{2.5}$[7], $SO_x$ and $NO_x$[8] emitted by each power plant in Chile, which consider only mortality, morbidity and

levels of investment in renewable energies, higher or lower than the target. For example, Spain supports renewable energy through feed-in tariffs that are differentiated by technology. Because they set the feed-in tariff too high for PV solar, they surpassed the target of 500MW by more than 2,000MW (Barroso et al., 2010), increasing the overall cost of the policy.

[7] Particulates smaller than $2.5\mu m$

[8] We quantify only the effects of $PM_{2.5}$, $SO_x$ and $NO_x$ emissions. On the one hand, those are the pollutants that cause major concern (USEPA, 1995); on the other, there aren't any estimates of the marginal damage caused by other pollutants in Chile—carbon monoxide (CO), volatile organic compounds (VOC) and trace metals like mercury (Hg), nickel (Ni), vanadium (V), arsenic (As) and cadmium (Cd).

the reduction of agricultural yields. Muller and Mendelsohn (2007) estimate that these effects account for 94% of the total damage in the United States.[9]

We assume four locations where marginal damages differ because of population size (see table notes). We further assume that the value of the marginal damages in 2010 are the ones estimated by Cifuentes et al. (2010), but over time they converge to the ones estimated by Muller and Mendelsohn (2007) for the United States as Chile's GDP per capita gradually converges to USA's GDP per capita. While per capita damages are larger in the United States, the marginal damages of emissions are larger in Chile because population densities around the sources of emissions are larger in Chile.

Note that in equations (2) and (3) total damage is a function of emissions $t_i$. Nevertheless, in practice the damage is caused by the exposure of individuals and things (like buildings or crops) to pollution. As shown in Figure 2a, emissions interact with the local environment to determine the concentration of the pollutant in the air and only then humans and things are exposed and damaged.

The mapping between emissions and concentration is highly dependent on local conditions and even on the characteristics of each source. For example, Muller and Mendelsohn (2009) show that ground-level emissions in urban areas increase the concentration nearby more than high-stack emissions, because tall smokestacks disperse the pollution away from the source. On the other hand, they also show that in rural areas concentration levels do not depend on whether the emission occurs in ground level or in a high stack. This is one source of imprecision in the assessment of environmental costs.

Similarly, the mapping between exposure and immission on the one hand and damage on the other is subject to considerable uncertainty. Protracted exposition to pollution increases the prevalence of several chronic and acute diseases (morbidity), and lowers life expectancy (mortality). Both morbidity and life expectancy are influenced by many other factors and it is not easy to quantify the incremental contribution of pollution.

**The damage caused by $CO_2$ emissions** The adverse effects of climate change are floods, droughts, change in storm patterns, temperature, higher sea levels, among others, causing costs in those affected human activities. The marginal damage of $CO_2$ is the present value of all incremental economic costs (present and future), caused by the incremental climate change of emitting an additional ton of $CO_2$ into the environment. As Figure 2b shows, the damage caused by greenhouse gases does not depend on local conditions around the source, but only on the carbon content of the fuel burned.

Nordhaus (2010) estimated the price per ton of $CO_2$ for five post-Copenhagen scenarios using the RICE-2010 model. In our evaluations we assume that the marginal damages of $CO_2$ over time are the prices of $CO_2$ reported in Nordhaus' (2010) optimal scenario. This scenario maximizes economic welfare, assuming that all countries mitigate emissions optimally from 2010 on, equaling the marginal cost of reducing $CO_2$ to the marginal damage of $CO_2$ in all sectors of the economy. Therefore, in this case $CO_2$ prices can be interpreted as marginal damages. Table 2 exhibits the marginal damage of $CO_2$ emissions, estimated in Nordhaus (2010). The price of $CO_2$ increases over time and ranges from $0 in 2010 to $58.3 in 2069 per ton of $CO_2$.[10]

[9]Muller and Mendelsohn (2007) also include the damage to timber, materials, visibility and recreation.

[10]In the long term, the price of $CO_2$ in Nordhaus (2010) is capped by the price of the technology that can replace all carbon fuels. Nordhaus (2010) argues that the price of this technology is $1,260 per ton of carbon, which is equivalent to $343.3 per ton of $CO_2$. To convert from dollars per ton of carbon to dollars per ton of $CO_2$ divide by 3.67.

Finally, to compute the total damage of $CO_2$ we assume that the marginal damage is constant with power plant emissions but increases over time.

# 3 An evaluation of renewable quotas

## 3.1 A brief introduction into the Emma model

**Description and basic assumptions** Emma is an intertemporal integrated assessment model that minimizes the private expected cost of supplying electricity—the sum of capacity, operation and outage costs. Just as it is done in the CIS, in our model plants are dispatched by merit order and water from the Laja reservoir is used optimally.[11,12]

Existing capacity in 2010 is taken as given and, from then on, the model optimally installs new plants—hydro, coal, natural gas, diesel, nuclear and renewables. It also optimally chooses plant location in three different zones, that differ in population size and transmission costs. Available hydro projects are carefully modeled with a supply curve which we built with public information about water rights. We assume that renewables become gradually available over the years. The initial fraction of the renewable supply curve in Figure 3 is 20% in 2010 and this fraction increases linearly until discovering the total potential in 2025.

Precipitation uncertainty is modeled assuming four hydrologies (dry, intermediate, normal and wet), each one with independent probabilities that mimic the historical distribution of precipitation in the CIS. Fossil fuel price uncertainty is modeled with four equally-likely price vectors.[13]

Formally, if $r$ is the discount rate, $\pi$ is the probability of a hydrology-fuel price vector combination, $k(t)$ is the annuity payment of the total cost of the installed capacity in year $t$, $c(t)$ is the operation cost during year $t$ and $o(t)$ is the outage cost during year $t$, Emma minimizes

$$\sum_{t=1}^{60} \frac{1}{(1+r)^t} \sum_{j=1}^{16} \pi_j \cdot [k(t) + c_j(t) + o_j(t)] \tag{5}$$

subject to producing the energy demanded each year—given the prices that consumer's pay—and complying with renewable quotas and environmental standards. Notice that Emma is an intertemporal model, not a dynamic programming model—there are no reservoir level states and the optimization finds the vector that minimizes (5) over the whole planning horizon.

The simulations assume that the demand for electricity grows about 5% p.a. until 2020, and then at lower rates as the rate of GDP growth eventually converges to developed country levels.

**Demand responds to price** One novel feature of Emma is that both energy prices and consumption are endogenous, as the demand for power responds to the price of energy. This way, every year, installed plants are dispatched to fill the load duration curve of three types of customers—residential/commercial, regulated

[11] Laja is the only reservoir in Chile that has interannual storage capacity.

[12] There are also smaller reservoirs in the CIS that we model as run-of-river plants, whose availability varies in every demand block.

[13] We assume that coal and natural gas prices are positively correlated with the price of oil.

LV-HV (for low voltage and high voltage) and non regulated HV—, which determines the system's marginal costs and expected spot prices. Residential clients pay a regulated energy tariff, called BT1. The BT1 tariff is obtained from the sum of the expected marginal costs, the capacity cost and the distribution cost, adjusted by average losses. Regulated LV-HV and non regulated HV clients pay separate tariffs for energy and capacity during peak hours. The energy price for LV and HV clients is equal to the expected marginal cost, also adjusted by average losses and the capacity cost is distributed pro rata as an energy charge during the peak load block; Given those prices, the demanded quantities during each block match the produced quantities every year—the model iterates until it finds the market's equilibrium. Because it is assumed that the price each client pays during a demand block is constant, the quantity of energy demanded during each block is deduced directly from the capacity demanded at each instant during the respective block.

**From planning to markets** Cost minimization is equivalent to competitive behavior. This is a plausible assumption in the CIS because, in the short run, the Economic Load Dispatch Center (CDEC for its Spanish acronym) centrally dispatches plants according to strict merit order to meet load at every moment. Dispatch is mandatory and independent of contractual obligations, which ensures competitive behavior in operation given plant installed at each moment in time. Then, in the long run, free entry of generation ensures cost minimization. Consequently, marginal projects earn zero profits, because electricity prices are calculated directly from the shadow prices of the constraints of serving the quantity of energy demanded each year.[14] At the same time, hydro and renewables obtain Ricardian rents because their supply curves are upward sloping.

It should be noted that in Chile's CIS, a significant fraction of the water rights, which are necessary to build hydro plants, are owned by Chile's main generator, Endesa. Moreover, Endesa has a strategic alliance with Colbún, another generator who owns water rights, to jointly develop a large project in the Aysén region in southern Chile.[15] Emma has a module that models the joint strategic behavior of Endesa and Colbún, assuming that they expand their installed capacity to maximize their joint profits. Nevertheless, in this paper we assumed divested water rights that ensure competition among all generator companies. We make this assumption because our interest in this paper is to model the effect of renewable quotas, not the exercise of market power.

## 3.2 Scenarios

To estimate the effects of renewable quotas we simulated the following scenarios:

- **Baseline:** No obligations to generate with renewable energy are ever adopted.
- **10% renewable quota:** An obligation of supplying at least 5% of annual sales of electricity with renewable energy in 2010, gradually increasing to 10% in 2024 is adopted.

[14] The strong duality theorem ensures that, using those shadow prices, marginal projects earn zero profits.

[15] We estimate that Endesa's water rights account for 22% of the total hydro potential in GWh/year and that Endesa + Colbún's water rights account for the 47%. The last number includes the water rights owned by Endesa, Colbún, and HidroAysén.

- **20% renewable quota:** An obligation of supplying at least 5% of annual sales of electricity with renewable energy in 2010, gradually increasing to 20% in 2020 is adopted.

The baseline scenario corresponds to the cost minimizing expansion and operation of the CIS, without policies that encourage renewables. New plants install pollution abatement equipment to comply with the current environmental standard—the Environmental Impact Evaluation System (SEIA for it's Spanish acronym). The SEIA forces the installation of abatement equipments for pollutants to ensure a certain air quality. The abatement efficiency imposed to each plant varies within technologies and location.

The 10% renewable quota scenario forces a quota of 10% of renewable energy as stated in the Chilean law, which forces generators to supply at least 5% of their annual sales of electricity with renewable energies in 2010, to gradually reach 10% by 2024.[16,17] The 20% renewable quota scenario assumes that the obligation is raised to 20% in 2020.[18] (This is currently being discussed in the Congress.)

We also simulated two benchmarks to calibrate the impact of environmental policies:

- **Uncontrolled emissions:** No environmental policies are ever adopted.
- **Optimal environmental policy:** Under this policy the marginal operation cost of fossil fuel plants equals their social cost, i.e., the private cost plus the marginal damages of emissions per MWh ($PM_{2.5}$, $SO_x$, $NO_x$ and $CO_2$).

The uncontrolled emissions scenario removes all existing abatement equipment and simulates how the CIS would expand if no environmental policies were in place. The intention behind this is to compare the magnitude of the environmental effects of the proposed policies with those of the current regulation.

The optimal scenario, on the other hand, minimizes the cost of supplying electricity, internalizing the externalities caused by emissions. This estimates how much further environmental policies may go. Of course, the results depend on the assumptions of the values of the marginal damages, and therefore are subject to uncertainty.

## 3.3 Results

### 3.3.1 The effects on $CO_2$ emissions

Figure 3 plots $CO_2$ emissions over time with each of the five policies. One can clearly distinguish two periods. During the first 20 years (between 2010 and 2030), $CO_2$ emissions remain flat at about 13 million tons per year with all policies but the optimal. From then on, $CO_2$ emissions grow in every case, but which policy is adopted significantly changes emissions' growth. Why are renewables seemingly ineffective to reduce

[16] Note that this applies to contracted energy since 2010. Between 2020 and 2021 most contracts signed before 2010 will expire and the law will apply to the renewed contracts. In 2021 the law will apply to all contracts.

[17] The current law establish that generators that do not comply with the requirement must pay for each noncompliant MWh. Nevertheless, in this paper we assume that all generators comply with the requirement.

[18] In this case, the law applies to all contracts, not depending on when the contract was signed.

emissions for so long? The standard intuition is that a renewable quota substitutes a clean technology for fossil fuels. Our results show that the standard intuition is misleading. Why?

Figure 4 shows the composition of generation over time for four scenarios: baseline, 20% renewable quota, uncontrolled emissions and optimal. At the bottom of each graph are the technologies that do not emit $CO_2$ and air pollutants: renewables and hydro. At the top are the technologies that emit $CO_2$ and air pollutants: coal, LNG, and diesel. Panel (a) in Figure 4 shows that in the baseline case demand increases are supplied mainly with investments in hydro. Because hydro capacity also stimulates plants fired with natural gas (an efficient means to hedge against droughts), coal capacity freezes and $CO_2$ emissions remain constant.

Comparison of panels (a) and (c) show that with a quota of 20% the share of renewables quickly rises. Nevertheless, until 2030 the share of fossil fuels is almost indistinguishable from the baseline case, because renewables substitute hydro investments. Because of this, renewables are almost useless to reduce $CO_2$ emissions before 2030.

Consider next what happens after 2030. Note that $CO_2$ emissions trend upward in the baseline case, as the share of coal starts to increase because profitable hydro projects run out. As Figure 3 shows, now renewables become effective to reduce $CO_2$ emissions. Indeed, after 2030, the quota of 20% seems to be as effective as the optimal policy. Thus, while emissions in the baseline case reach 140 million tons by 2049, they are 40% lower under the 20% renewable quota obligation. Renewables become effective only after 2030 precisely because the quota slowed down investments in hydro capacity. Eventually (after 2030) water is used and this slows down investments in coal. Consequently, the share of coal in generation falls. The general lesson is that the impact of renewable quotas on $CO_2$ emissions is highly dependent on the specifics of each case.

Figure 3 might also suggest that a renewable quota is quite close to the optimal policy. Nevertheless, a comparison of panels (c) and (d) in Figure 4 shows that this impression is wrong. The optimal policy expands hydro capacity as fast as possible. Then, when water runs out, the system expands with LNG and the share of coal falls precipitously. By contrast, with a quota water develops much more slowly.

Renewable quotas also reduce emissions by inducing falls in consumption (the so-called energy efficiency effect). As we discussed in section 2.1, they raise the cost of electricity and, of course, the prices that consumers pay, reducing the quantity demanded of electricity. With a renewable quota of 20%, prices in the long term are approximately 30% higher than in the baseline case, decreasing the quantity of electricity demanded by approximately 12%.[19] Nevertheless, this does not explain the total reduction of $CO_2$ emissions achieved. Changes in the composition of generation are much more important.

The modest contribution of energy efficiency to reductions in emissions is confirmed by examining the optimal policy. Note that prices are higher than in the baseline case because the policy internalizes the social cost of externalities (prices are approximately 23% higher in 2049 with the optimal policy). Consumption decreases approximately by 9%, which reduces emissions. Nevertheless, as with renewable quotas, most of the decrease in $CO_2$ emissions comes from changes in the composition of generation. As Figure 4 (d) shows, hydro projects are developed at a faster rate and the policy induces the substitution of combined cycle natural gas plants for coal plants, which have a lower $CO_2$ emission intensity factor.

[19] Benavente et. al (2005) estimated that the residential long term price elasticity of electricity of the CIS is -0.39. This is the price elasticity that we used in our simulations.

### 3.3.2 Local pollution

Tables 3a and 3b show the added emissions of air pollutants and their social cost with each of the five policies. Renewable quotas affect emissions of local pollutants, but their impact is modest. As can be seen in Table 3b, with a 20% renewable quota $SO_x$ emissions fall by 38%, $NO_x$ by 38% and $PM_{2.5}$ by 19%. But the impact over the social cost of pollution is much lower—pollution environmental cost is reduced only by 18%. Again the explanation is in Figure 4, panels (a) and (c): for 20 years renewable energies substitute hydro, barely affecting the share of fossil fuels. Only after 2030 they substitute generation with coal.

It is interesting to compare the effect of renewable quotas with the effect of the current environmental regulation on the one hand and the optimal policy on the other. A renewable quota reduces air pollution, but still far from optimal levels. Indeed, the optimal policy is to reduce air pollution rapidly. Again, the comparison between panels (c) and (d) in Figure 4 is revealing: with the optimal policy investments in hydro occur faster than in the baseline case, and once hydro runs out, the system expands with LNG instead of coal, which pollutes less. This substitution of LNG for coal does not occur with renewable quotas. On the other hand, the optimal policy induces the installation of abatement equipment, sometimes with higher efficiencies than those imposed by the current regulation, so fossil fuel plants instantly emit less.

The relative ineffectiveness of renewable quotas can also be appreciated by comparing the baseline case with the uncontrolled emissions case (column 4 in Table 3). Current environmental policies (SEIA), are aimed at controlling emissions of local pollutants, particularly particulate material ($PM_{2.5}$). Note that the current environmental policies are quite effective in cutting emissions of local pollutants. Were it not for them, emissions of $SO_x$ would be 4 times higher; $NO_x$ emissions would be 2 times higher; and $PM_{2.5}$ emissions would be 30 times higher. All in all, the social cost of local pollutants would be about 4 times larger (see Table 3).

### 3.3.3 Economic effects

Most analysis of the economic effects of renewable quotas quantify the incremental costs wrought by the policy. The first two lines of Table 4 present total system costs in present values for 2010-2049, in millions of dollars.[20]

Consider the 10% renewable quota. It increases private generation costs from US$51,126 million to US$51,334 million and, as we have already seen, reduces environmental costs by about 11%, from US$5,028 million to US$4,497 million. Total costs fall slightly, just 0.6%. With a 20% quota, private production costs increase by about 5%, and environmental costs fall a further 10%. Total costs increase, but again the change is small, 2.1%. Thus, the impression one gets by looking at costs is that renewable quotas have modest effects.

Nevertheless, a thorough assessment of the economic impact of a quota should compute its deadweight loss. By definition, the deadweight loss of a policy relative to the baseline is

$$\text{deadweight loss} = \Delta\,(\text{consumer surplus}) + \Delta\,(\text{generators profits}) - \Delta\,(\text{environmental costs})$$

The middle panel of Table 4 reports such calculation.

[20] All results are expressed in US dollars at 2009 price levels.

Note first that a renewable quota of 10% imposes a negligible excess burden—US$69 million over 40 years. This occurs because during the first 10 to 15 years the requirement can be met with "cheap" renewable energy—the initial part of the supply curve depicted in Figure 1.

One might think that an increase of the quota to 20% has modest effects on deadweight loss, but this is wrong. Indeed, deadweight loss increases 55 times, to US$3.8 billion. Why? The arithmetic is that consumers lose about US$9.4 billion, which is partly compensated by the fall in environmental costs (US$1.3 billion) and the increase in generators' profits (about US$4.3 billion). The economics is that the supply curve of renewable energy is steep and the quota considerably raises the price of the marginal renewable source and, of course, the subsidy paid to renewable energy.

The subsidy to renewable energy, as equation (1) shows, depends on two factors: the premium for renewable energy ($p^r - p^m$) and the quantity demanded ($q^r$). Figure 4 shows the price of renewable energy, taken from the supply curve, with quotas of 10% and 20%, and the market price of electricity in the baseline. Note that with both quotas, the premium for renewable energy is zero during the first years, hence renewable energy is not subsidized during those years. However, the quota of 20% starts subsidizing renewable energy 4 years earlier than the quota of 10%, and in most years the premium is more than 2 times larger than the premium of a 10% quota. On the other hand, a quota of 20%, of course, doubles the quantity demanded of renewable energy. Therefore, as equation (1) suggests, the subsidy wrought by a quota of 20% is always more than 2 times the subsidy of a quota of 10% and, most of the time, it multiplies the subsidy of a quota of 10% by a factor higher than 4.

Once this fact is recognized, the rest follows. Higher prices for renewable energy inevitably increase the price that consumers pay—hence the large fall in consumer surplus. At the same time, the increase in the price of renewable energy rises generators' profits. Last, because the quota finally slows the expansion of fossil fuel technologies after 2030, environmental costs fall.

What do we learn from all this? One lesson is that system costs, even if environmental externalities are valued, are misleading indicators of the social cost of policies. With quotas prices increase, demand responds to price changes and the quantitative impact of these responses is important.

The second general lesson is that the impact of policies on welfare is nonlinear. The economics is simple: supply curves of renewable energy are not flat but upward sloping. Thus, policy assessments must carefully estimate the availability of renewable energy sources and their costs.

The third lesson is that renewable quotas redistributes wealth from consumers to producers. If the supply curve of renewable energy is steep, the size of this redistribution will be large. More than that, quotas also redistribute wealth within producers. The last three lines of Table 4 show that the owners of renewables will increase their profits at the expense of the rest of generators.

### 3.4 Which technologies does a renewable quota substitute?

To end this section we provide a simple explanation why renewable quotas only substitute base load technology.

Remember the well known basic economics of the optimal technology mix for electric utilities[21]. To simplify, assume perfect competition, deterministic behavior of supply and demand, and two technologies: base load and peak load. Assume that the annualized costs of capacity per kW for base load is $k_b$ dollars and $k_p$ dollars for peak load. Marginal operating costs per kWh are $c_b$ dollars for base load and $c_p$ dollars for peak load, and, as is standard $k_b > k_p$ and $c_b < c_p$.

Figure 4 (a) shows a standard load duration curve and the total cost of a kW of base load and peak load capacity per year as a function of the running hours. The classic result is that optimal running time (in hours) for peak load technology over a year is

$$t^* = \frac{k_b - k_p}{8.760 \cdot (c_p - c_b)}$$

Note that the total cost of supplying a load with duration longer than $t^*$ hours is smaller using a base load plant than a peak load plant, so the minimizing cost criteria will choose to supply loads longer than $t^*$ with base load capacity and the remaining with peak load capacity. In Figure 4 (a), $B$ MW of base load and $P$ MW for peak load capacity will be installed to supply demand at minimum cost.

Figure 4 (b) shows the same load duration curve and the costs of the same base load and peak load plants, but assumes that $R$ MW of renewable energy are necessary to comply with the renewable quota. Because the running cost of renewables is very low, they are first in the merit order. Hence, once a quota is introduced, base and peak load capacity face a residual demand, which is obtained by shifting down the load duration curve in $R$ MW. However, the optimal running time $t^*$ remains the same, because it only depends on costs. Therefore, $B' = B - R$ MW of base load capacity and $P$ MW of peak load capacity will be built to minimize the total cost of supplying electricity. The renewable quota substitutes for investments in base load capacity (hydro, coal, nuclear or combined cycle gas fired plants as the case may be), and it will substitute peak capacity (gas or diesel turbines) if the requirement is large enough.

While this example is simple, it captures the main effect. When demand and supply are uncertain (see Chao, 1983 and 2011), the optimal running time of each technology is determined by the annual costs of capacity, the average availability, marginal operating costs and the expected fraction of time where demand is higher than the sum of available supply. Then, with a renewable quota, the optimal running time of base load technologies (their $t^*$'s) will be modified because intermittent renewable energy sources like wind and solar will be installed to meet the quota. Bushnell (2010) and Chao (2011) show that stochastic effects imply that a renewable quota requires more peak load capacity and less base load capacity. However, the results over energy generation are larger for base capacity because each MW of base load capacity runs for more hours in a year than a peak load MW.

[21] See Turvey (1968), Crew and Kleindorfer (1971), and Wenders (1975).

# 4 Conclusion: characterizing cost-effective environmental policies

We began this paper claiming that renewable quotas are likely to be ineffective to reduce $CO_2$ emissions and pollution. Using our intertemporal integrated assessment model Emma and a simple application of the optimal technology mix for electric utilities, we have shown that a renewable quota substitutes mainly investments in base load technologies. As a result, renewable quotas are ineffective to reduce emissions in many systems where there are "cheap" available hydro resources to invest in base load capacity. Even when renewables substitute for coal generation, quotas may be very expensive because renewable supply curves are upward sloping, hence the cost increases nonlinearly with the size of the quota. To conclude, we briefly characterize cost effective environmental policies and contrast them with renewable quotas.

There are two ways to reduce pollution and greenhouse gas emissions. One is capturing emissions directly and the other substituting "clean" technologies for emission-intensive technologies. Both mechanisms are complements and environmental policies can be thought as rules and incentive structures that induce combinations of both.

One widely-used policy is to impose emission standards. If binding, standards either force the installation of abatement equipment or, if abatement equipment is infeasible or too costly, the abandonment of the technology.

Standards are cost-effective when abatement equipment is cheap relative to the environmental benefits they achieve. Chile's SEIA, a twenty-year old policy, which forced the installation of abatement equipment, is a case in point. As Column 4 in Table 3b shows, it has cut $SO_x$ emissions by a factor of four, halved $NO_x$ emissions and reduced $PM_{2.5}$ emissions to one-thirtieth. And it has been a remarkably cost effective policy. As Column 4 in Table 4 shows, SEIA increases social surplus in about US$5 billion (around 10% of the system's cost) and barely increases the cost of supply (US$50.8 billion with no standards to US$51.1 billion in the baseline case).

Now while SEIA has large welfare effects, it barely takes advantage of fuel substitution. As can be seen by comparing panels (a) and (b) in Figure 4, the composition of generation in the baseline case (with SEIA) and with uncontrolled emissions is almost the same.[22] Moreover, SEIA does little to cut $CO_2$ emissions. This is why there would still be room for an optimal policy, which would substitute low-emission fuels for high-emission fuels, and fully internalizes environmental externalities.

Again, we can see the effects of the optimal environmental policy over investments using the basic economics of power systems. Figure 4 (c) shows the case in which base load technology is a "clean" technology (e.g. water) and the peak load technology pollutes and emits $CO_2$ (e.g. coal). The optimal policy increases the marginal operation cost of the peak load technology, changing it's optimal running time from $t^*$ to $t'$. Therefore, "dirty" peak load capacity decreases from $P$ to $P''$, decreasing emissions to the optimal levels. This explains why in the optimal policy hydro projects are developed faster and, once hydro runs out, LNG substitute for coal, as LNG emits less $CO_2$ and air pollutants. Also, the optimal policy stimulates the installation of pollution abatement equipment when convenient, making the policy even more effective. Last, panels (a) and (d) in Figure 4 show that the optimal policy would dramatically change the composition of

[22]Moreover, SEIA neither addresses greenhouse gas emissions nor makes any difference.

generation. Essentially LNG substitutes for coal generation, whose share in total generation would steadily fall.

The contrast of these two policies with renewable quotas is stark, because quotas are expensive and do not achieve sizable reductions of pollution and $CO_2$ emissions. This is primarily because they neither force abatement nor fuel substitutions. Therefore, they do not directly affect the emission factors of any of the technologies in the system, and since they only substitute part of the generation with base load capacity, the reductions they can achieve are limited. Worse, they may substitute renewables for hydro, achieving no environmental benefits at all.

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## Table 1
## Availability and costs of non-conventional renewable energies in Chile's CIS

| | Small hydro 1[6] | Small hydro 2 | Small hydro 3 | Wind 1[7] | Wind 2 | Wind 3 | Bio-mass 1 | Bio-mass 2 | Bio-mass 3 | Bio-gas[8] | Geo-thermal 1[9,10,11] | Geo-thermal 2 | Geo-thermal 3 | PV Solar[12] | Solar thermal[12] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Capacity factor | 60% | 60% | 60% | 30% | 25% | 20% | 90% | 90% | 90% | 90% | 72% | 72% | 72% | 30% | 30% |
| Exploration's success prob. | - | - | - | - | - | - | - | - | - | - | 30% | 15% | 5% | - | - |
| Available capacity (MW)[1] | 267 | 544 | 333 | 150 | 300 | 1,050 | 325 | 650 | 2,274 | 350 | 150 | 300 | 1,050 | 1,051 | 500 |
| Available Energy (GWh/year)[2] | 1,404 | 2,858 | 1,748 | 394 | 657 | 1,840 | 2,562 | 5,123 | 17,931 | 2,759 | 941 | 1,883 | 6,590 | 2,762 | 1,314 |
| Investment US$/kW (plant) | 2,467 | 2,467 | 2,467 | 2,409 | 2,409 | 2,409 | 3,500 | 3,500 | 3,500 | 2,828 | 3,964 | 4,556 | 6,923 | 6,325 | 5,260 |
| O&M in US$/kW-year (plant)[3] | 20 | 20 | 20 | 32 | 32 | 32 | 68 | 68 | 68 | 68 | 173 | 173 | 173 | 12 | 60 |
| Average distance to transmission system (km)[4] | 40 | 60 | 80 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 65 | 65 | 65 | 3 | 3 |
| Investment US$/kW (transmission)[5] | 798 | 2,284 | 6,580 | 211 | 211 | 211 | 562 | 562 | 562 | 562 | 715 | 715 | 715 | 357 | 357 |
| Investment in US$/MWh | 50 | 50 | 50 | 108 | 130 | 162 | 52 | 52 | 52 | 42 | 79 | 91 | 138 | 283 | 236 |
| O&M in US$/MWh | 4 | 4 | 4 | 12 | 15 | 18 | 9 | 9 | 9 | 14 | 29 | 29 | 29 | 5 | 23 |
| Variable fuel costs in US$/MWh | - | - | - | - | - | - | 31 | 70 | 103 | 64 | - | - | - | - | - |
| Other variable costs in US$/MWh | - | - | - | 8 | 8 | 8 | - | - | - | - | - | - | - | - | - |
| Transmission in US$/MWh | 16 | 46 | 132 | 10 | 11 | 14 | 8 | 8 | 8 | 8 | 13 | 13 | 13 | 15 | 15 |
| Total costs US$/MWh | 70 | 100 | 186 | 137 | 163 | 202 | 100 | 139 | 172 | 128 | 121 | 133 | 180 | 303 | 273 |

Notes: (1) In each case, except for hydropower, the availability was taken from UTFS (2008). We assume that between 2010 and 2026 the available capacity of all technologies increases linearly from 20% to 100%. (2) $(\text{available energy}) = (\text{available capacity}) \times (\text{capacity factor}) \times 8{,}760$. (3) Fixed operation and maintenance costs come from EIA (2010). (4) Average distances come from our own estimations. (5) In each case, the cost of connecting a NCRE plant to the system, in USD/kW, was estimated assuming it corresponds to a transformer at the plant and a transmission line in 110kV between the plant and the nearest substation. For small hydro plants, the transmission costs were estimated by minimizing the cost of each project. We report average values. (6) The available capacity and energy of small hydro plants was estimated through the study of the granted water rights, that aren't yet in use. To calculate the LCOE of each project the following parameters of each plant were considered: water flow rate, hydraulic head, location, distance to transmission system and the average capacity factor of the already existing plants located near the water right. Small hydro 1 considers projects that range from 49 – 86 US$/MWh. Small hydro 2 considers projects between 86 – 140 US$/MWh. Small hydro 3 considers projects between 140 – 197 US$/MWh. (7) The cost of a wind turbine comes from Pavez (2008) and was adjusted by CPI's variation. The capacity factors supposed for wind turbines exceed the ones deduced by numerous studies ordered by the CNE. See Galetovic and Muñoz (2008). (8) CNE and GTZ Consultants (2009). The investment cost is the average value of the GTZ study, assuming plants smaller than 6 MW. (9) The investment costs of geothermal power plants is obtained from the following formula: let $I$ is the total investment cost conditional to success in the exploration, let $\pi$ be the probability of success and $\lambda$ the fraction of the investment that takes place after a successful exploration. Then, the total expected cost of a kW of geothermal is $\lambda I + \frac{(1-\lambda)}{\pi} I$. We assume $\lambda = 0.95$ and $I = 3{,}550$ US$/kW. (10) To date, there are 10,715 MW of geothermal capacity installed around the world, and it is expected that they'll generate 67,246 GWh (average capacity factor of 71.6%). See Holm et al. (2010). (11) We are currently working on a more precise estimate of Chile's geothermal potential and costs. (12) The investment cost of a kW of solar energy comes from EIA (2010). (13) The rest of the parameters come from estimations obtained in interviews with experts.

**Table 2**
**Marginal damages caused by $CO_2$ and pollutants**
**(In US$/ton)**

| | (1) $CO_2$ | (2) $PM_{2.5}$ | (3) $SO_2$ | (4) $NO_X$ |
|---|---|---|---|---|
| Nordhaus | 0 to 58.3 | - | - | - |
| Big city[1] | - | 29,679 | 434 | 4,268 |
| Small city[2] | - | 8,330 | 138 | 1,228 |
| Town[3] | - | 325 | 5 | 42 |
| M&M[4] (EE.UU.) | | 3,220 | 1,310 | 260 |
| M&M[5] urban | - | 3,300 | 1,500 | 300 |
| M&M[5] rural | | 1,100 | 900 | 300 |

Source: $CO_2$: Nordhaus (2010). $PM_{2.5}$, $SO_2$ y $NO_X$: from Cifuentes et al. (2010).
Notes: (1) Percentile 90 of the estimated damage. (2) Percentile 60 of the estimated damage. (3) Percentile 30 of the estimated damage. (4) Muller and Mendelsohn, (2009). (5) Muller and Mendelsohn (2007).

**Table 3a**
**Emissions and environmental costs of air pollutants and $CO_2$**

| | *(1)* *Baseline* | (2) 10% renewable quota | (3) 20% renewable quota | (4) Uncontrolled emissions | (5) Optimal |
|---|---|---|---|---|---|
| Added emissions (thousands of tons) | | | | | |
| SOx | *3,902* | 3,405 | 2,696 | 16,390 | 916 |
| NOx | *6,436* | 5,438 | 4,018 | 14,758 | 1,469 |
| PM 2.5 | *173* | 160 | 140 | 5,233 | 18 |
| $CO_2$ | *1,611,631* | 1,347,196 | 969,617 | 1,863,702 | 761,038 |
| Environmental costs (present values in millions of US$ dollars) | | | | | |
| SOx | *282* | 254 | 215 | 1,035 | 78 |
| NOx | *848* | 757 | 633 | 1,699 | 185 |
| PM 2.5 | *657* | 646 | 626 | 4,260 | 25 |
| Total cost of pollution | *1,787* | 1,657 | 1,474 | 6,994 | 288 |
| $CO_2$ | *3,241* | 2,839 | 2,255 | 3,654 | 1,884 |
| Total environmental costs | *5,028* | 4,497 | 3,728 | 10,647 | 2,172 |

**Table 3b**
**Emissions and environmental costs of air pollutants and $CO_2$ relative to baseline**

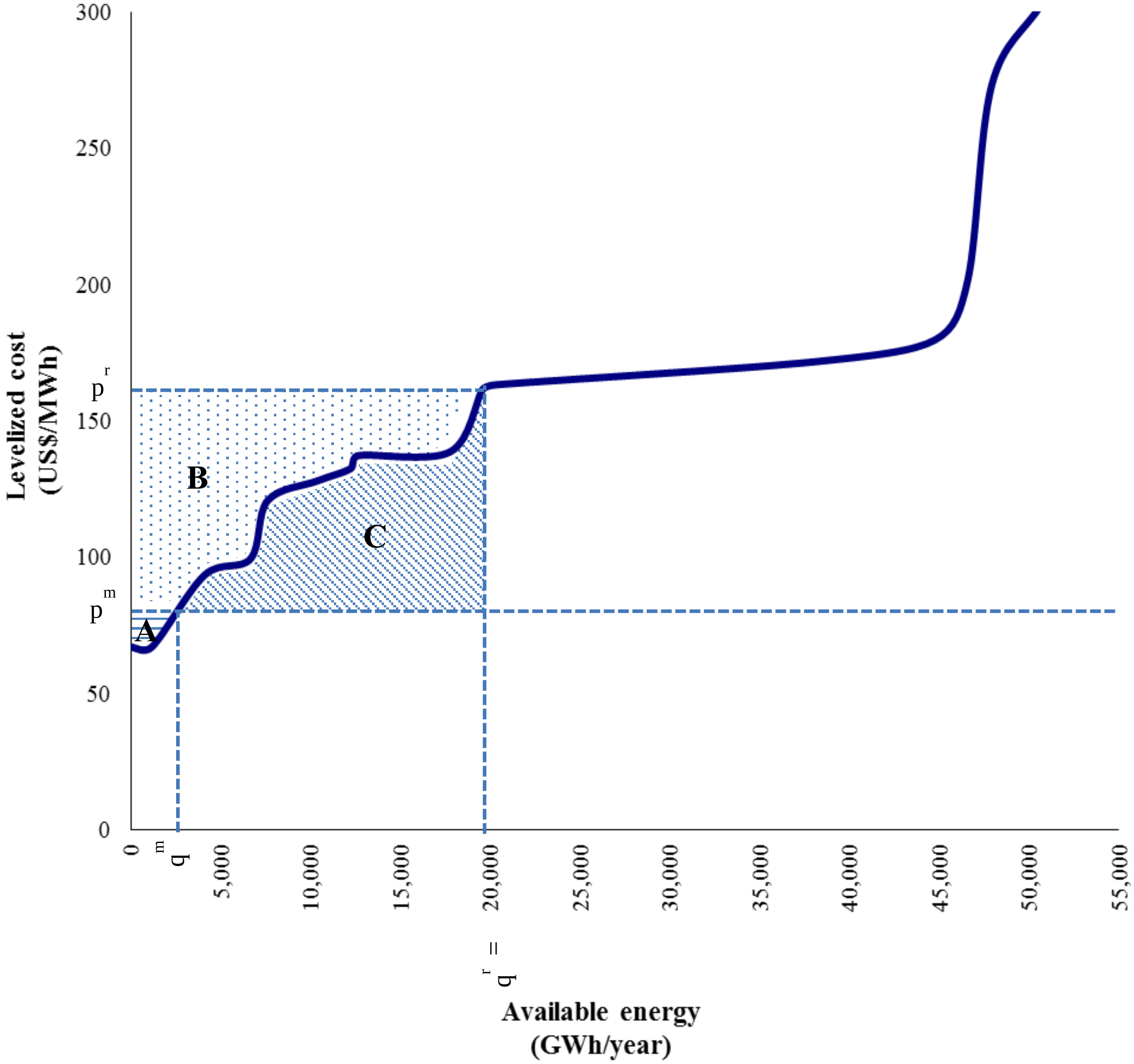
| | *(1)* *Baseline* | (2) 10% renewable quota | (3) 20% renewable quota | (4) Uncontrolled emissions | (5) Optimal |
|---|---|---|---|---|---|
| Added emissions | | | | | |
| SOx | *100%* | 87% | 69% | 420% | 23% |
| NOx | *100%* | 85% | 62% | 229% | 23% |
| PM 2.5 | *100%* | 92% | 81% | 3,018% | 10% |
| $CO_2$ | *100%* | 84% | 60% | 116% | 47% |
| Environmental costs | | | | | |
| SOx | *100%* | 90% | 76% | 367% | 28% |
| NOx | *100%* | 89% | 75% | 200% | 22% |
| PM 2.5 | *100%* | 98% | 95% | 648% | 4% |
| Total cost of pollution | *100%* | 93% | 82% | 391% | 16% |
| $CO_2$ | *100%* | 88% | 70% | 113% | 58% |
| Total environmental costs | *100%* | 89% | 74% | 212% | 43% |

## Table 4
## The economic effects of environmental policies
## (2010-2049, present values in millions of US$ dollars)

| | *(1)* *Baseline* | (2) 10% renewable quota | (3) 20% renewable quota | (4) Uncontrolled emissions | (5) Optimal |
|---|---|---|---|---|---|
| System's cost[1] | *51,126* | 51,334 | 53,588 | 50,810 | 50,805 |
| Environmental costs[2] | *5,028* | 4,497 | 3,728 | 10,647 | 2,172 |
| Total | *56,154* | 55,831 | 57,316 | 61,458 | 52,977 |
| Δ Environmental costs | *0* | -531 | -1,299 | 5,619 | -2,856 |
| Δ Generators' profits | *0* | 1,075 | 4,277 | -816 | 616 |
| Δ Consumer surplus | *0* | -1,675 | -9,376 | 1,482 | -3,506 |
| Change in social surplus[2] | *0* | -69 | -3,800 | -4,954 | 2,138 |
| Δ Renewable generators' profits | *0* | 1,459 | 6,750 | -61 | 187 |
| Δ Hydro generators' profits | *0* | -61 | -882 | -777 | 2,030 |
| Δ Fossil fuel generators' profits | *0* | -323 | -1,591 | 22 | -1,601 |
| Generators' profits | *5,257* | 6,332 | 9,534 | 4,440 | 5,873 |

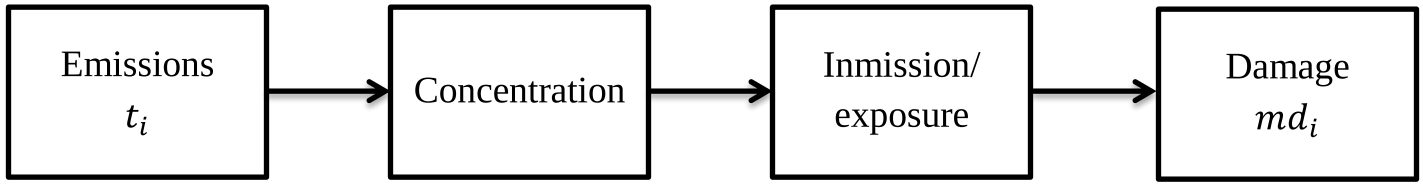
[1] System's cost is the sum of investment and operation costs of generation.
[2] Environmental costs is the sum of social cost of pollution and $CO_2$.
[3] Δ Social surplus = Δ Consumer surplus + Δ Generators' profits - Δ Environmental costs.

## Figure 1
## The non-conventional renewable energy supply curve



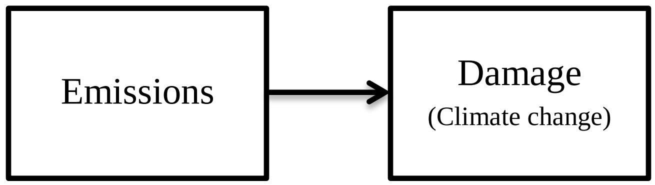
# Figure 2
# The mapping between emissions and damage

### (a) Local pollutants



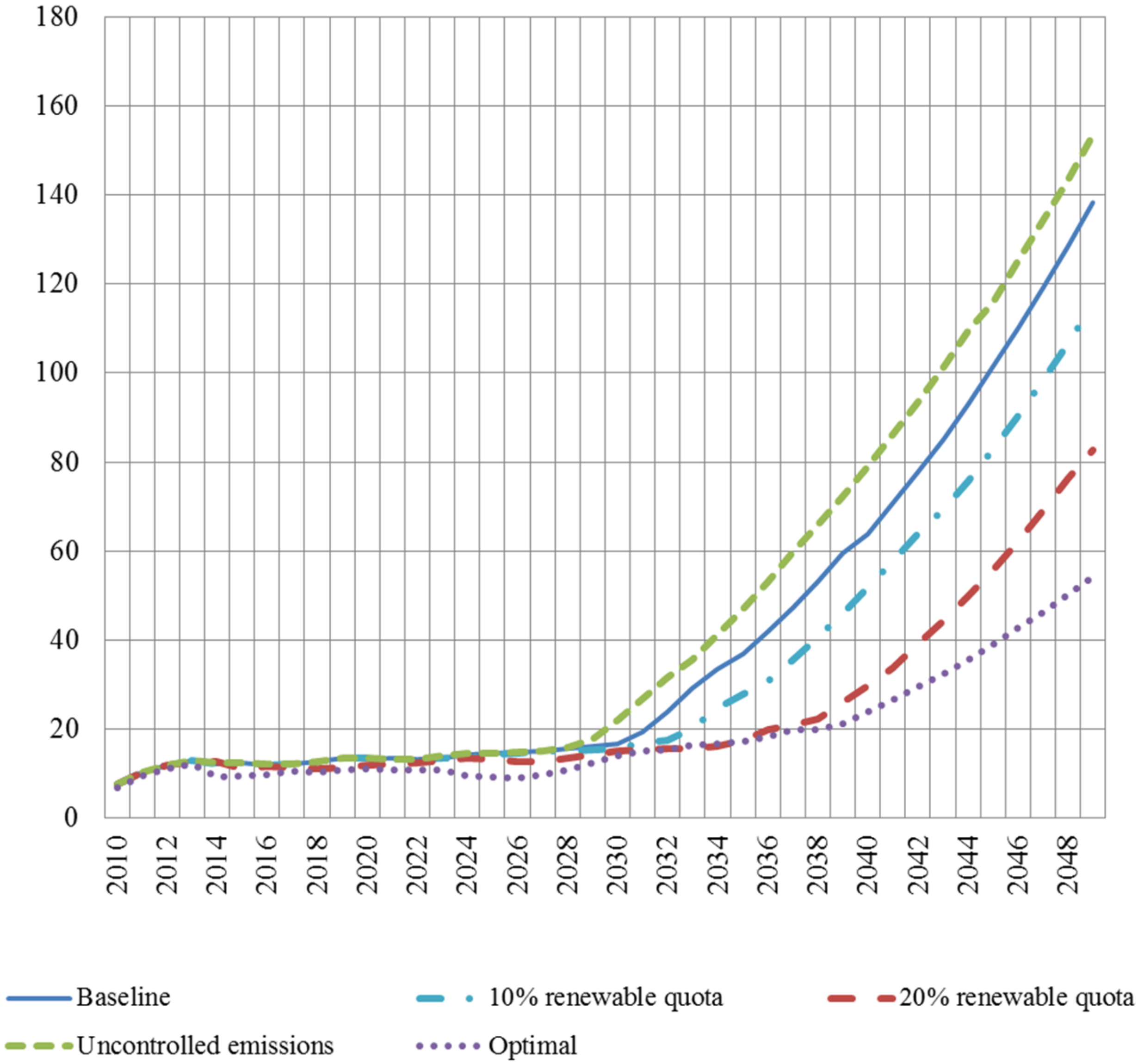

We assume a direct relation between emissions ($t_i$) of pollutant $i$ and the marginal damage it causes ($md_i$). In practice, emissions of local pollutants interact with the local environment and affect concentrations. Damage depends on inmissions or exposure to the pollutants.

### (b) Greenhouse gases

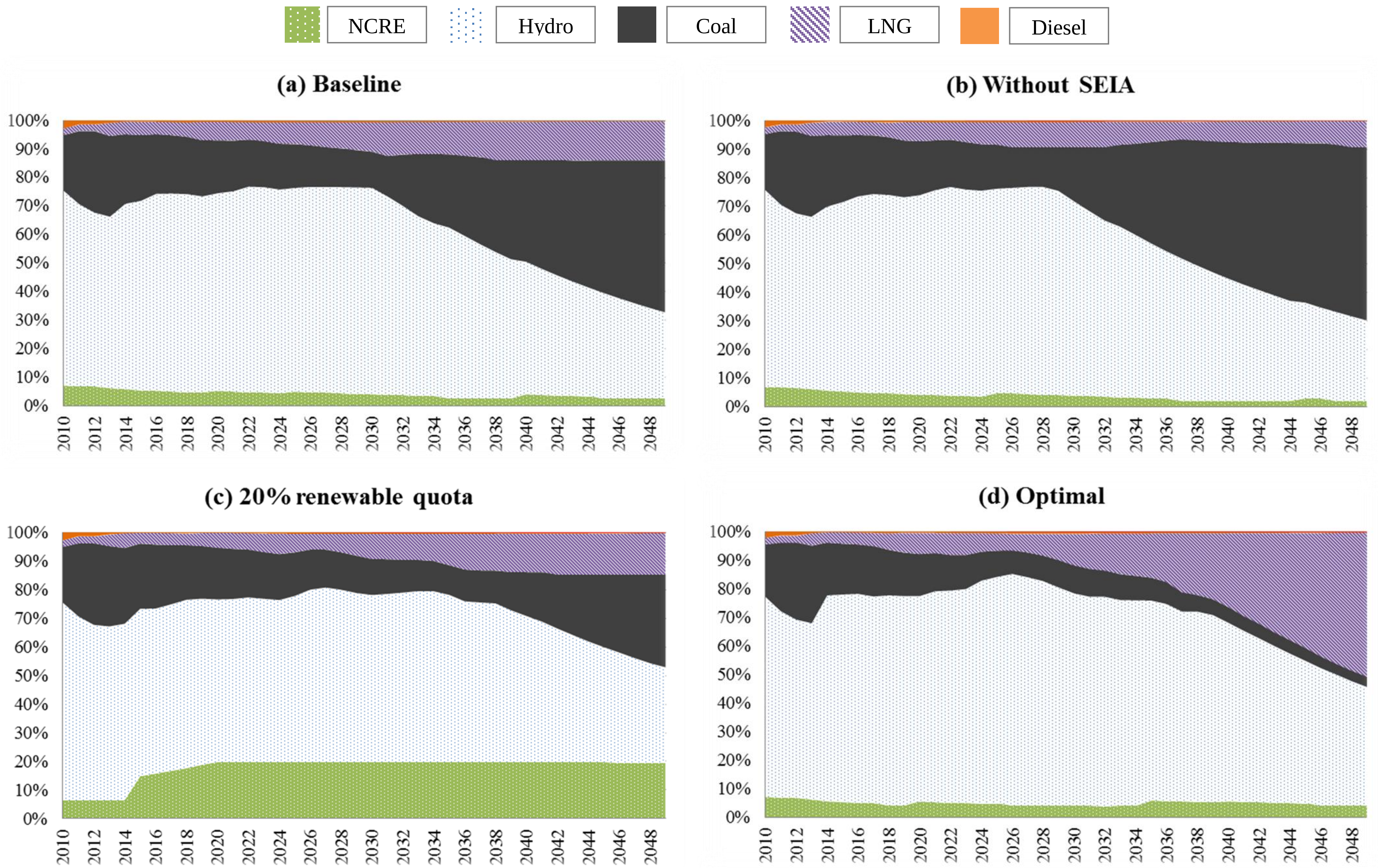



The damage caused by greenhouse emissions is global, and is a direct function of the carbon content of the fossil fuel burned.

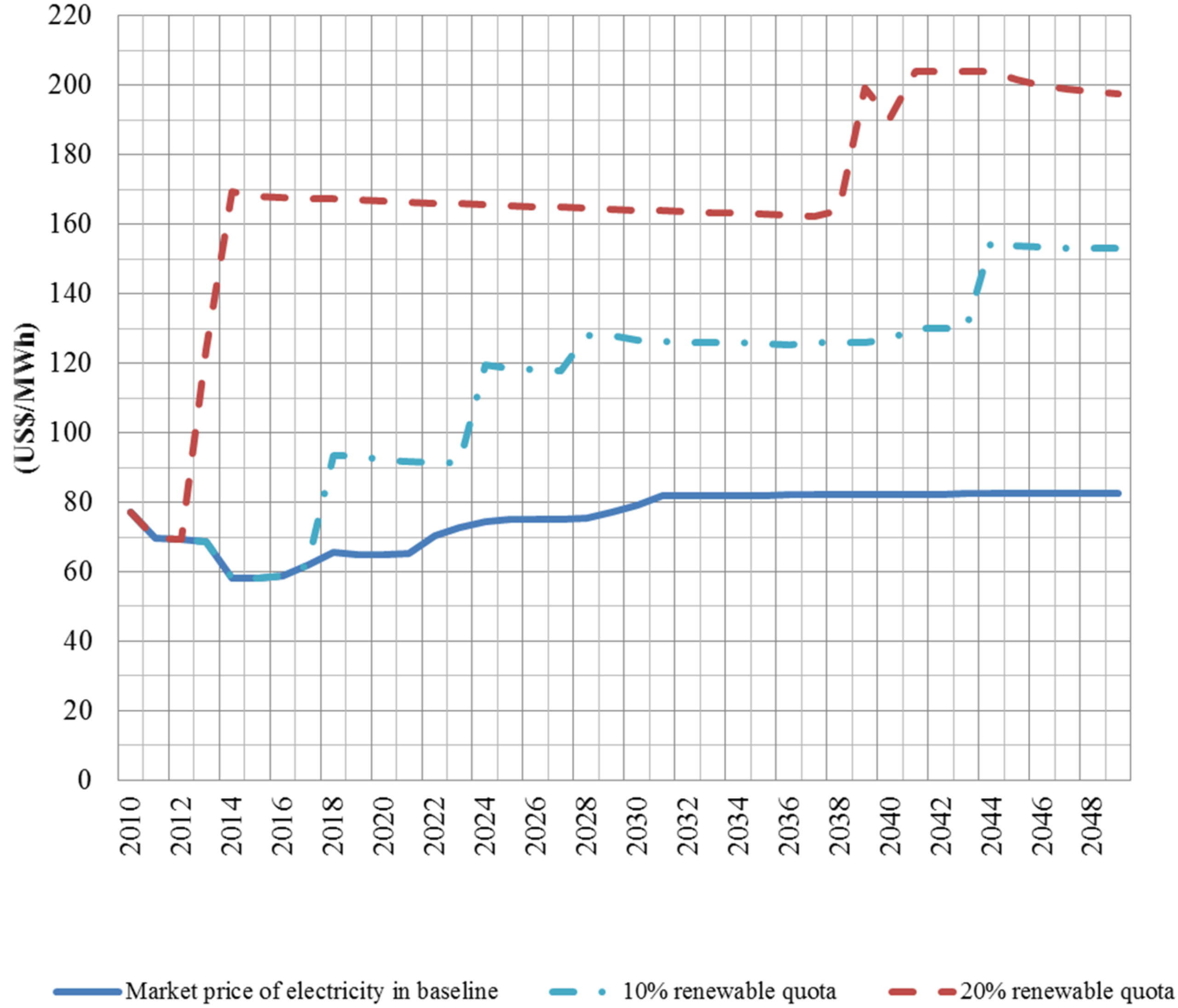
**Figure 3**
**$CO_2$ emissions**
**(millions of tons per year)**



## Figure 4 – The composition of generation under alternative policies

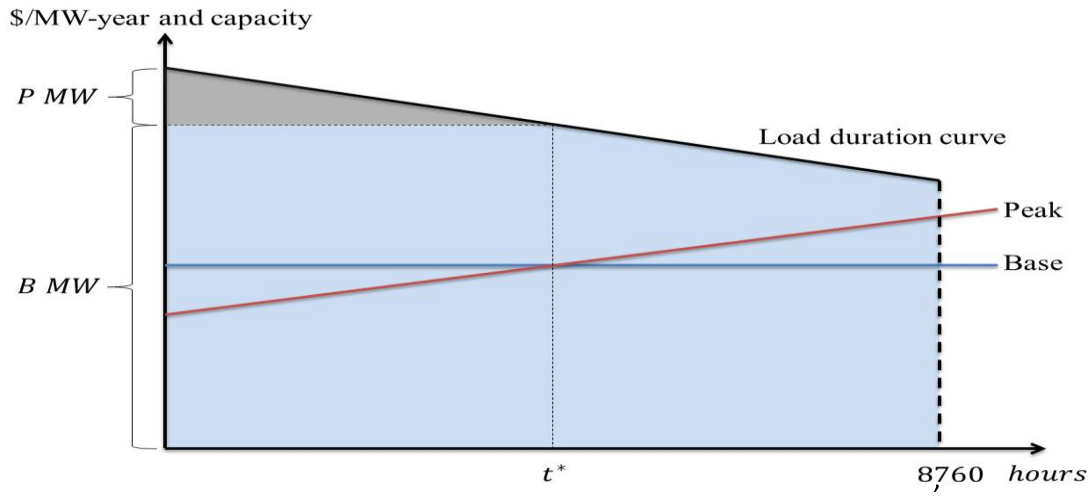


## Figure 5
## The equilibrium price of renewable energy

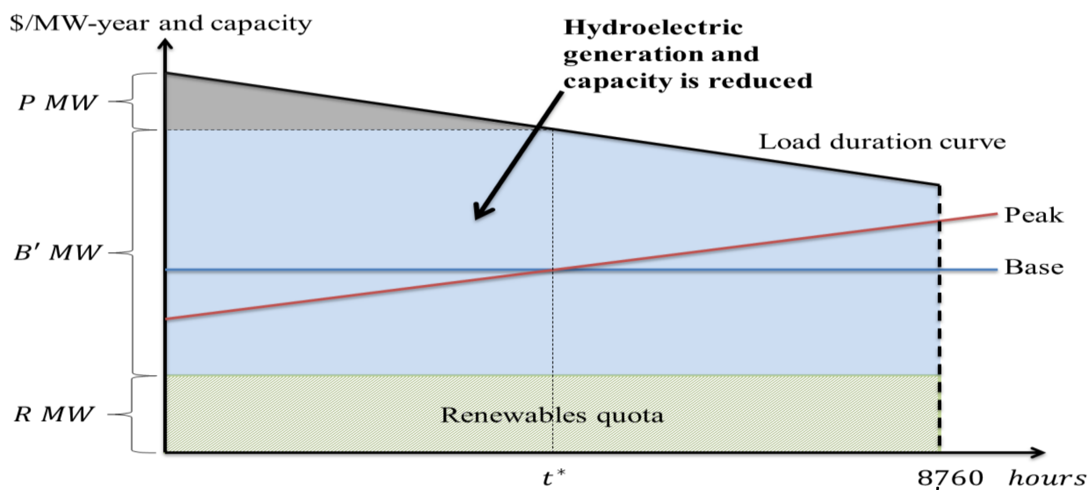


## Figure 6 – How environmental policies affect the composition of generation

(a) Baseline




(b) Renewable quota




(c) Optimal