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Wind, Coal, and the Cost of Environmental Externalities

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Abstract

We compare the cost of generating electricity with coal and wind in Chile's Central Interconnected System (SIC). Our estimates include the cost of marginal damages caused by coal plant emissions. On average, we estimate that the levelized cost of coal, including externalities, is \$84/MWh. It is efficient to abate emissions of air pollutants (SO_x, NO_x and $PM_{2.5}$) but not of CO_2. Then the cost wrought by environmental externalities equals \$23/MWh or 27% of total cost. Depending on the price of coal, the levelized cost of coal may vary between \$72 and \$99/MWh. The levelized cost of wind is \$144/MWh with capacity factor of 24%. This cost includes the cost backup capacity to maintain LOLP, which equals \$13/MWh or 9% of total cost. The levelized cost of wind varies between \$107/MWh with capacity factors of 35% to \$217/MWh with capacity factors of 15%.

We conclude that wind is competitive only when it achieves capacity factors around 35% and coal prices are very high. So far the average annual capacity factor achieved by existing wind farms in Chile has been less than 20 %, which suggests why wind has developed only slowly.

Keywords: Environmental economics, Externalities, Power generation planning, Wind power generation.

JEL Classification No.: O13, Q51, Q56.

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Wind, coal, and the cost of environmental externalities

Alexander Galetovic, Cristián M. Muñoz

Abstract— **We compare the cost of generating electricity with coal and wind in Chile's Central Interconnected System (SIC). Our estimates include the cost of marginal damages caused by coal plant emissions.**

On average, we estimate that the levelized cost of coal, including externalities, is \$84/MWh. It is efficient to abate emissions of air pollutants (SO_x, NO_x and $PM_{2.5}$) but not of CO_2. Then the cost wrought by environmental externalities equals \$23/MWh or 27% of total cost. Depending on the price of coal, the levelized cost of coal may vary between \$72 and \$99/MWh.

The levelized cost of wind is \$144/MWh with capacity factor of 24%. This cost includes the cost backup capacity to maintain LOLP, which equals \$13/MWh or 9% of total cost. The levelized cost of wind varies between \$107/MWh with capacity factors of 35% to \$217/MWh with capacity factors of 15%.

We conclude that wind is competitive only when it achieves capacity factors around 35% and coal prices are very high. So far the average annual capacity factor achieved by existing wind farms in Chile has been less than 20 %, which suggests why wind has developed only slowly.

Index Terms—**Environmental economics, Externalities, Power generation planning, Wind power generation,**

I. INTRODUCTION

Many hope that nonconventional renewable energy---wind, solar, small hydro, ocean and biomass---will stem the growth of fossil fuel electricity generation and reduce greenhouse gas emissions. Nevertheless, so far only a tiny fraction of world electricity is generated with nonconventional renewables and even fewer projects would be undertaken, were it not for a myriad of incentive schemes that have been introduced all over the world.[1] Critics of incentive schemes argue that nonconventional renewables are more expensive. Supporters answer that we need subsidies, tax credits and quotas because fossil fuel generators do not pay for the environmental damage they cause. This paper contributes to this discussion by comparing the levelized cost of coal and wind in Chile's Central Interconnected System (SIC) including the costs caused by pollutants.[2]

To compare the cost of coal and wind we replace a 260 MW coal power plant with a wind farm that produces the same average quantity of energy per year and compute the differential trajectory of system costs over the next 25 years. Such an exercise poses at least three challenges.

The first challenge is to take account of the environmental costs wrought by coal generation. Coal plants emit sulfur oxides (SO_x), nitrogen oxides (NO_x) and particulate matter (PM), which damage health, materials, visibility and crops. Furthermore, they release CO_2, the main greenhouse gas, which causes global warming. We use standard estimates of emission factors for coal plants and the marginal damage caused by each pollutant to compute the levelized cost of coal.

Second, wind capacity factors vary across locations and availability is volatile.[3] We account for plant capacity factors with measurements from eight different locations in Chile where wind speeds were registered hourly for periods longer than a year. We also estimate the costs of the thermal backups which are needed to maintain LOLP with higher wind generation.[4]

Third, dispatch rules imply that a wind farm does not replace coal generation one-by-one at each moment. Indeed, because Chile's SIC is a hydrothermal system and dispatch is cost-based according to merit order, wind is part of the base load, while coal plants are turned off when hydro generation is abundant. In addition, strictly speaking investments in wind farms do not replace investments in conventional technologies (hydro and fossil-fuel), but delay them instead. To include these nuances in our cost calculations we assume that conventional plats serve the residual load after wind generation (i.e. the load that remains after subtracting wind generation), recalculate the optimal entry plan of conventional technologies and then simulate system operation for the next 25 years.

We estimate that the levelized cost of coal, including the cost of efficient abatement, is on average \$23/MWh. When added to capital and fuel costs, the levelized cost of a MWh generated with bituminous coal is \$84/MWh. Of course, the

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[1] So far 118 countries have introduced a mechanism to support renewable energy and at least 96 countries have set formal or informal generation targets. See Renewable Energy Policy Network for the 21st Century (2011).

[2] The SIC is the country's main electricity system About 55% of installed capacity is hydroelectric.

[3] For example, Díaz-Guerra (2007) reports that in Spain, who generates nearly 9% of its electricity with wind, hourly generation varied between 25 MW (almost nothing) to more than 8,000 MW in 2007.

[4] The loss of load probability (LOLP) is one measure of system reliability. It is defined as the probability that system load cannot be supplied by net generation: LOLP = pr(load > net generation) .

levelized cost varies with the price of coal: from \$72/MWh for inexpensive coal at \$50/ton up to \$99/MWh with coal at \$120/ton.

On the other hand, we estimate that the levelized cost of a wind farm with capacity factor 24% (the average deduced from wind measurements in Chile) is \$144/MWh. This cost is mainly the result of combining “high” investment costs in turbines with “low” capacity factors. Even with capacity factors as high as 35%, wind is not competitive (\$107/MWh). By contrast, the cost of maintaining LOLP, \$13/MWh, is only 9% of the mean total production cost (Of course, wind’s volatile availability may stress the transmission system; we do not consider this here.)

The rest of this article is organized as follows: Section II calculates the environmental costs of a coal plant. Section III describes the determinants of wind’s cost. Section IV briefly describes the Chile’s SIC and our methodology. Section V presents the results.

II. THE ENVIRONMENTAL COSTS OF COAL

A. *Emission Factors*

Conventional or pulverized coal plants (PC) generate electricity through a series of conversion stages. In simple terms, coal is burned to boil water and produce high-pressure steam. Steam, in turn, moves a turbine that generates electricity.

Total emissions depend on, among others, the type of coal (e.g. bituminous or sub-bituminous coal), the type and size of the boiler, the condition of the burners and, most importantly, the efficiency of the abatement equipment.[5] The main pollutants emitted when burning coal are sulfur oxides (SO_x), nitrogen oxides (NO_x) and particulate matter (PM). Uncontrolled PM emissions include ash and coal residues. Depending on its size, particulate matter is classified as PM_{10} (between 10 and 2.5 μm) and $PM_{2.5}$ (smaller than 2.5 μm).[6,7] In addition, coal combustion releases greenhouse gases, mainly CO_2.

Table I reports maximum and minimum emission factors in kg of pollutant per ton of fuel burned, the standard way of reporting them. Emission factors make it simple to obtain the total amount of pollutants released into the atmosphere:

$$(\text{kg of emissions}) = (\text{tons of coal}) \times (\text{emission factor})$$

Panel (a) shows “uncontrolled” emission factors---emissions when no abatement equipment is installed--- for coal plants; panel (b) shows controlled emissions; panel (c) shows the amount of emissions captured with abatement equipment and not released into the atmosphere. Last, panel (d) shows uncontrolled emissions of fuel oil Nr. 6 backup turbines.

TABLE I
EMISSION FACTORS FOR COAL AND OIL (IN KG/TON)[1,2,3]

	SO_x	NO_x	PM_{10}	$PM_{2.5}$	CO_2
(a) Uncontrolled emissions (no abatement)					
Maximum	22.8	16.5	38.5	6.1	2,385
Minimum	18.6	3.6	7.8	0.5	2,165
(b) Controlled emissions (with abatement)					
Maximum	2.3	3.3	0.2	0.2	426
Minimum	1.9	0.7	0.04	0.02	271
(c) Emissions abated					
Maximum	20.5	13.2	38.3	5.9	1,959
Minimum	16.7	2.9	7.7	0.4	1,894
Efficiency	90%[4]	80%[5]	99%[6]	99%[6]	82%
(d) Uncontrolled emissions, (fuel oil Nr 6)					
Maximum	22.3	6.4	0.8	0.9	3,386

Notes: (1) We calculated emission factors for SO_x, NO_x and PM for coal with data contained in U.S. EPA (1998), tables 1.1-3; 1.1-6; 1.1-7 and 1.1-9. (2) We calculated mission factors for fuel oil Nr. 6 with data contained in U.S. EPA (1998), tables 1.3-1; 1.3-4 and 1.3-12. (3) We calculated emission factors for CO_2 with data contained in IPCC (2005, table 8.1, p. 343), which reports CO_2 emissions per MWh. To obtain emissions per ton of coal we assumed that 0.34 tons of coal generate one MWh. Note that CO_2 abatement is still experimental. (4) Wet scrubbers (FGD): abatement efficiency > 90%. (5) Selective Catalytic Reduction (SCR): abatement efficiency between 75% and 86%; we assumed 80%. (6) Electrostatic precipitator (ESP): abatement efficiency = 99%.

Even a cursory look at Table I reveals that the amount of pollutants released into the atmosphere is much lower with abatement equipment. In Chile, environmental norms that cap emissions of SO_x, NO_x, and PM are stringent enough to force the installation of abatement equipment in coal plants. Indeed, we will see next that this is the efficient policy because the marginal damage caused by emissions is larger than the cost of abatement.

B. *The Marginal Damage of Emissions: Air Pollutants*

The standard way of measuring the costs caused by emissions is by computing marginal damages per ton of pollutant released into the atmosphere. The marginal damage caused by a pollutant is the incremental cost borne by society when one additional ton is released into the atmosphere; or the damage avoided by reducing emissions in one ton.

Air pollutants---SO_x, NO_x and PM---mainly affect the area surrounding the source, and damage health, materials, crops and visibility. Because roughly 90% is damage to the health of individuals, and per capita damages depend on the levels of concentration of pollutants in the atmosphere, marginal damage is roughly a linear function of the population around the source. This is not to say that estimates are precise, however.

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[5] In Chile the caloric content of bituminous coal is roughly 6,350 kCal/kg. The caloric content of sub-bituminous coal is roughly 4,000 kCal/kg.

[6] This is the largest value reported by NEC in its node price reports.

[7] Muller and Mendelsohn (2007) and World Bank (1998) point out that $PM_{2.5}$ is inhaled into the lungs were is causes serious damage to human health. More information on other pollutants is available from the U.S. Environmental Protection Agency, US EPA (1998).

TABLE II
ORDER STATISTICS FOR MARGINAL DAMAGES
(IN $/TON)

	(1) SO_x	(2) NO_x	(3) $PM_{2.5}$	(4) C (Tol)	(5) CO_2 (Tol)	
Mean	344	3,085	20,714	59	16	Mean
SD	629	5,642	38,244	77	21	SD
CV	1.82	1.83	1.85	1.31	1.31	
Min	1	11	71	–110	–30	Min
10	1	15	93	–26	–7	10
25	9	83	529	4	1	25
Median	88	783	5,117	44	12	Median
75	419	3,726	24,915	95	26	75
90	1,048	9,337	63,501	154	42	90
Max	9,924	92,230	627,774	573	156	Max

Note: The order statistics are from the distributions generated by 10.000 trials. Marginal damages of air pollutants (SO_x, NO_x and $PM_{2.5}$) were sampled jointly from a Fischer-Tippet distribution fitted to the data reported by Cifuentes et al.(2010). Marginal damages of C and CO_2 come from a Fischer-Tippet distribution which replicated the order statistics reported by Tol (2011).

One source of imprecision is that the mapping between emissions and pollutant concentration depends on local conditions and the characteristics of each source. For example, Muller and Mendelsohn (2009) show that ground-level emissions in urban areas increase concentrations nearby more than high-stack emissions, because tall smokestacks disperse pollutants away from the source.

It adds to the imprecision that the mapping between exposure to a pollutant 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). However, both morbidity and life expectancy are influenced by many other factors and it is not easy to disentangle the incremental contribution of pollution.

Last, the value of the damage depends on estimates of lifetime earnings, which vary from country to country.

Be that as it may, our source is Cifuentes et al's (2010) estimate of marginal damages per ton of SO_x, NO_x and $PM_{2.5}$ around 76 Chilean fossil-fuel plants. They repeatedly measured emissions and concentrations around each plant, built one distribution of marginal damage for each pollutant and plant and reported the 5th, 50th and 95th percentile of each distribution. To obtain our estimate we built the distribution of the 95th percentile of each pollutant across the 76 plants. We computed the correlation matrix across pollutants and sampled 10,000 combinations of marginal damages with Cristal Ball. Table II show the order statistics of the distribution wrought by the 10,000 combinations.

Note that the range of variation of the marginal damage of each pollutant is wide---the coefficient of variation around the mean value is slightly larger than 1.81. This reflects mainly regional variation: in Chile power plants are located in many different locations, some with large populations and some with few inhabitants. In our estimates we used the average value---. more or less equivalent to assuming that new coal plants are sited randomly.

TABLE III
THE MARGINAL DAMAGE OF POLLUTANTS
AND THE COST OF ABATEMENT

(a) $ per ton				
	SO_x	NO_x	$PM_{2.5}$	CO_2
Marginal damage	344	3,085	20,714	16
(b) Cost of abatement[1,2,3]				
	SO_x	NO_x	$PM_{2.5}$	CO_2
$ per kW	172	83	70	-
$ per ton	336	251	451	71
(c) Marginal damages and cost of abatement in $ per MWh				
	SO_x	NO_x	$PM_{2.5}$	CO_2
Uncontrolled	2.7	17.3	42.7	13.0
Cost of abatement	2.4	1.2	0.9	48.8
Controlled	0.2	3.5	1.1	2.3
Net gain of abatement	0.1	12.6	40.7	–38.1
Abate?	yes	yes	yes	no
(d) Marginal damage of fuel oil No. 6				
	SO_x	NO_x	$PM_{2.5}$	CO_2
$ per MWh	2.0	5.2	4.7	12.7

Notes: (1) We obtained costs of abating NOx and SOx from World Bank Group (1998, p. 423), in 1997 US dollars, and converted them to $/2010 with CPI. Maximum values are used. (2) We obtained costs of abating PM from industry information. (3) We calculated the cost of abating one ton of CO_2 from IPCC (2005, Table TS.10, p. 43). Mitigation costs include capture, transport and geological storage. We used the maximum value.

Panel (a) in Table III, which reproduces the first line in Table II, shows marginal damages per ton of pollutant released into the atmosphere. The damage caused by NO_x and $PM_{2.5}$ is quite high. For example, according to Muller and Mendelson (2007, p. 10, Table 3) in the United States the marginal damage caused by a ton of NO_x is on average $300, and $3,300 for a ton of $PM_{2.5}$. By contrast, Muller and Mendelsohn estimate that the marginal damage caused by SO_x emissions is $1,500 on average, between four and five times the damage estimated by Cifuentes et al. (2010) in Chile.

In any case our estimates of the marginal damage of air pollutants are conservative. One reason is that we sampled marginal damages from the 95th percentile of the distribution for each plant and location. Another is that the largest marginal damages would be caused by plants installed in or close to Santiago, Chile's capital, where more than 6 million live. No coal plant would get environmental clearance to be installed in Santiago---siting is not random and is biased away from highly populated areas. Last, because the distribution of marginal damages is skewed to the right, the mean of the distribution of the marginal damage of each air pollutant is well above the median, around the 70th percentile.

Table III, panel (b) reports the cost of abatement per kW of investment. Note that a coal plant costs about $2.000/kW without abatement equipment; installing that equipment for the three air pollutant would cost $321/kW, increasing investment costs about 16%.[8] Would that pay? The second row in panel (b) reports costs per ton of pollutant abated, assuming that the equipment lasts 25 years, the discount rate is 10%, and a coal plant generates 1,900 GWh per year. It can be seen that the average cost per abated ton of NO_x and $PM_{2.5}$ is small relative to marginal damages, but similar for SO_x.

It is useful to compute damages per MWh, and compare them with the levelized cost of electricity. To calculate damages per MWh, one has to compute the number of kg released into the atmosphere per MWh generated. Because 0,34 tons of coal generate one MWh, it follows that

$$(\text{kg per MWh}) = (0{,}34\text{ tons}) \times (\text{emission factor})$$

is the total amount of the pollutant emitted when generating one MWh. The marginal damage wrought by one MWh is

$$(\text{marginal damage per kg}) \times (\text{kg per MWh})$$

It may seem obvious, but it is important that the marginal damage per MWh depends on the emission factor, which can be reduced drastically by installing abatement equipment.

Panel (c) of Table III reports damages per MWh. As a benchmark, consider the levelized cost of coal ignoring environmental externalities, which we estimate in $61/MWh (see Table V in section 5). If no emissions were abated, they would add $62.7/MWh to the private cost, thus doubling the cost of coal. Nevertheless, the per-ton cost of abating NO_x and $PM_{2.5}$ is small relative to the damages they cause and abatement is very effective, so that the optimal policy is to install abatement equipment. And once emissions of air pollutants are abated, marginal damages per MWh fall dramatically, and add a modest $4.8/MWh to the levelized cost of electricity. All in all, abatement increases social surplus in $59.7/MWh at the cost of $4.5/MWh, a gain of $55.2/MWh.

C. *The Marginal Damage of Emissions: CO_2*

According to Richard Tol (2011) as of 2010 there were 311 estimates of the marginal damage of a ton of carbon in 61 different studies.[9] Estimates vary a lot, despite that all are based on 9 estimates of the total economic impact of climate change (Tol, 2012) and 238 of the 311 estimates (three out of four) were made by one of three authors, Richard Tol (184), Chris Hope (77) or William Nordhaus (12).

To assess this uncertainty, Tol (2011) fitted a Fisher-Tippett distribution to the 311 estimates. The mean of the resulting distribution is $177/tC, with standard deviation $293/tC and mode $49/tC. While large estimates skew the distribution to the right, 25% of the distribution's mass is negative---i.e. according to the estimate, global warming *increases* welfare.

In addition, differences across classes of studies are systematic. For example, the mean of the distribution of marginal damages reported in peer-reviewed journals, $80/tC (standard deviation = $109/tC, $n = 220$) is smaller than the mean of the the distribution of marginal values reported in unpublished work, $296/tC (standard deviation = $442/tC, $n = 91$). At the same time, the mean of the distribution of estimates after 2001 is $113/tC, (standard deviation = $153/tC, $n = 217$) which is smaller than the mean of the distribution of estimates reported between 1995 and 2001, ($113/tC, standard deviation = $227/tC, $n = 67$), which in turn is smaller than the mean of the distribution of earlier studies, $299/tC (standard deviation = $522/tC, $n = 27$). More important, the smaller the pure rate of time preference (the rate used to discount the future), the higher the average estimate of the marginal damage. Thus with a 3% pure rate of time preference, the mean of the distribution is $19/tC (standard deviation = $18/tC, $n = 76$); it increases to $84/tC (standard deviation = $93/tC, $n = 76$) when the rate is 1%; and to $276/tC (standard deviation = $258/tC, $n = 53$) when the rate is 0%. This suggests that a significant part of the differences in estimates can be traced back to disagreement about the pure rate of time preference.[10]

To move forward we choose Tol's (2011) mean estimate of $59/tC, which implies valuing the damage of an additional ton of CO_2 into the atmosphere in $16 (in Table II, column (4) we show the order statistics of this distribution). This estimate is rather conservative (unless a rate of time preference of 3% seems excessive). In any case, one should mention that Nordhaus (2008) estimates that the marginal damage of carbon emissions will increase between 2% and 3% per year. Thus, while he estimated a cost of $27/tC ($7.4/tCO_2) in 2008, his estimate for 2050 is $90/tC ($24.5/tCO_2), and $200/tC ($54.5/tCO_2) in 2100.[11]

We obtained the cost of abating CO_2 in a coal power plant from the report by the IPCC Working Group III, IPCC (2005). Abatement costs include capture, transport and geological storage and are valued at $48.8/MWh. Beyond of the fact that carbon capture seems to be expensive compared with the current marginal damage, technologies are still experimental, so that for the time being it seems that the only feasible policy is to release CO_2. Thus, the damage wrought by CO_2 emissions is $13/MWh, the cost of uncontrolled emissions.

D. *Valuing the Environmental Damage of Coal*

It follows that our estimate of the marginal damage of coal generation assumes that air pollutants are abated but CO_2 is not. Then our estimate is

$$\$4.8/\text{MWh} + \$13.0/\text{MWh} = \$17.8/\text{MWh}\,.$$

Note that almost three fourths of the estimate of damage is the global impact of CO_2 emissions.

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[8] Note that abatement equipment uses energy thus increasing the plant's consumption from about 4% of gross energy to about 7%.

[9] Studies typically report the marginal damage of a ton of carbon (C). One ton of CO_2 contains 1/3.67 tons of carbon (C). Thus, if the marginal damage of a ton of carbon is, say, $59/tC, the marginal damage of a ton of CO_2 is $\frac{\$59}{3.67} = \$16{,}1$.

[10] See Nordhaus (2007a, b) for expositions of how the pure rate of time preference affects marginal damage estimations.

[11] This value is slightly less than the price at which emissions permits are being traded in Europe. However, this price is influenced by multiple factors, including the quantity of emissions reductions set as a goal in the Kyoto Protocol. Therefore, we prefer to base our calculations on estimates of the social cost of CO_2 emissions.

TABLE IV
COST OF INSTALLING 1.65 MW VESTAS V 82 TURBINES

	173 MW	91 MW	58 MW
Total cost ($ million)			
Turbine	309	163	104
Construction	98	54	36
Total	407	216	140
Cost per kW ($)			
Turbine	1,783	1,793	1,806
Construction	566	589.7	617.1
Total	2,350	2,383	2,423

Source: Pavez (2008).

III. WIND

A. *The Cost of Wind Capacity*

Cost estimates for wind capacity are not very accurate and, at any rate, vary from project to project due to differences in scale, land cost and construction costs. In the United States, Bolinger and Wiser (2008, p. 21) argue that the cost per kW of wind installed in the U.S. in 2007 varied from $1,240 to $2,600, with a mean of $1,710. The average estimate from Bolinger and Wiser (2007) of the cost of that were projects proposed in 2006 (but at the time were still not executed) is that each kilowatt would cost $1,920.

In Chile, Moreno *et al*. (2007) estimated that each kW of wind nominal capacity cost between $1,100 and $1,500. Santana (2006), on the other hand, gives a range between $1,200 and $1,800. Endesa, the largest Chilean generator, reported that its 18 MW Canela wind farm cost $350 million ($1,928/kW) .[12] Barrick, a mining company, reported that its Punta Colorada 20 MW wind farm cost $40 million ($2,000/MW).[13]

Perhaps the most careful study of the cost of a wind farm in Chile is by Pavez (2008). Table IV shows the breakdown of Pavez's cost estimates for a wind farm in the north of Chile. According to column 1, a 173 MW wind farm would cost $407 million or $2,350/kW. The cost per kW increases as the size of the farm falls: the cost per kW is $2,383/kW for a 91 MW farm and $2,422.90/kW for a 58 MW farm. We assume that each kW of wind capacity costs $2,350.

B. *Capacity Factors and Wind Variability*

The variability of wind implies that propellers rotate below their maximum capacity. In practice, the capacity factor of wind turbines is comparatively low. [14]

TABLE V
CAPACITY FACTORS AT EIGHT MEASUREMENT POINTS

	(1) Heigth (m)	(2) Capacity factor (%)	(3) Initial month	(4) Final month
Loma del Hueso	20	39.5	09/06	11/07
Llano de Chocolate	20	7.7	06/06	11/07
Carrizalillo	40	16.3	07/06	09/07
Punta Los Choros	20	16.5	06/06	11/07
Lengua de Vaca	20	37.3	09/06	11/08
Cerro Juan Pérez	20	20.5	06/06	11/07
La Cebada Costa	20	33.6	06/06	11/07
Faro Carranza	40	26.7	01/06	01/07
Average (n = 15,568)		23.4		

Boccard (2009) reports that between 2003 and 2007 the average capacity factor in Europe was just 21%. Oswald *et al*. (2006) reports the following capacity factors: United Kingdom 28.4%, Spain 26.6%, Denmark 24.1% and Germany 17.8%. Bollinger and Wiser (2007) report capacity factors around 30% on average for the United States, although the range is broad—for example, between 18% and 48% for projects built in 2006. And EIA (2011), which surveys wind capacity and generation in 21 countries reports that in 2011 202,976 MW of nominal capacity generated 375,700 GWh---an average capacity factor of 21.1%.[15] This capacity factor is clearly representative: data from BPs 2012 *World Energy Outlook*, which reports world wind capacity and generation shows that since 1997 the yearly world average load factor has hovered between 17% and 21% without showing any trend.

In Chile NEC commissioned studies to measure wind speed at 15-minute intervals in eight different locations during more than a year (see Table V).[16] With reported wind speeds we calculated how many MWh a Vestas V66 2000/66 2MW onshore turbine would have generated every 10 minutes at each site. Then we added generation over one-hour intervals, took the average of capacity factors at the eight sites and obtained a 15,568 point distribution of hourly capacity factors. Last, with this distribution we built an hourly distribution of capacity factors for an "average" or "representative" year (8,760 hours) in an "average" or "representative" wind farm.

Table V shows the average capacity factors at each site. As can be seen from column 2, these vary between 7.7% (Llano del Chocolate) and 39.5% (Loma del Hueso) with an average of 23.4%, which is in line with observed capacity factors in other countries.

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[12] See "Endesa sale en defensa de centrales en Aysén por campañas ambientalistas", *Diario Financiero*, December 7, 2007.

[13] See "Molinos de energía", Special On-line Edition of El Mercurio, January 9, 2008.

[14] Low capacity factors are, in part, a consequence of design. In fact, a propeller's capacity factor can be increased with a large rotor and a very small propeller because in that case high capacity factors would be attained even if very little wind blows. However, this type of propeller would produce very little electricity. The best investment/generation ratio is achieved with larger propellers, but the result is lower capacity factors. The power curve of an aero generator is the ratio of power a turbine is capable of generating under different wind conditions. It is composed of an initial segment from wind speeds to *cut-in* speed such that there is no generation, followed by an almost linear segment with a positive slope that creates a constant power segment for a given range of speeds (between 15 and 25 m/s). Ultimately, for wind speeds greater than the *cut-out* limit, the turbine is disconnected and power generation returns to zero.

[15] See Table 2 in the Executive Summary.

[16] Studies on Chile's wind potential include studies by Corfo (1993) and Muñoz *et al.* (2003). Also see NEC (2007b).

Of course, these averages hide variation. The standard deviation of the 15,568 hourly capacity factors is 23.3% (coefficient of variation ≈ 1). The maximum is 100%, the minimum is 0%, and the interquantile range is 31% (= 35,9% – 4.9%). Moreover, the distribution is skewed to the right: the median capacity factor is 8.1 percentage points below the average at 15.2%.

Last, most wind blows between 4 and 7 PM, when hourly average capacity factors hover between 40 and 50%. By contrast, between midnight and 11AM they are uniformly below 10%.

IV. METHODOLOGY

A. *Substituting Wind for Coal*

To compare the cost of coal and wind we replace a 260 MW coal power plant with a wind farm that produces the same average quantity of energy per year. A 260MW coal plant generates about 1,900 GWh (capacity factor ≈ 83%). To replace it with a wind farm one needs roughly

$$\frac{1{,}900 \text{ GWh}}{(\text{wind capacity factor}) \times 8{,}760\text{h}}$$

MW of wind capacity. For example, if the capacity factor is equal to 23.4%, (the average of the 8 sites were NEC measured wind speeds), a 927 MW wind farm is needed to replace a 260 MW (gross) coal power plant.

B. *Simulating System Operation*

Estimating investment costs is simple---just multiply the number of kilowatts of capacity by the cost per kilowatt, a commonly available magnitude. By contrast, it is trickier to estimate coal's operation costs because under Chilean cost-based, strict merit-order dispatch rules coal plants are turned off when hydro generation is abundant. Moreover, hydro availability is stochastic.

For the same reason, it is not straightforward to estimate neither how much backup capacity you need to deal with wind's variability and maintain LOLP, nor how much the total cost of generation changes when you substitute a coal plant with a wind farm. Because wind availability varies, depending on the time of the day, day of the week or month of the year, wind could be substitute for coal, gas, fuel oil or reservoir water at the margin. Moreover, merit order dispatch implies that wind forms part of the base load, while coal plants are turned off when water is abundant. And whether a backup fuel oil turbine generates to absorb a shortage of wind depends on the current availability of water.

To simulate SIC's operation we use the Omsic dispatch model. Omsic is a stochastic dynamic programming model that optimizes the use of reservoir water (optimization stage), and then simulates plant dispatch under different realizations of water availability (simulation stage).[17,18] Omsic's monthly operation is simulated over 25 years (roughly the estimated life of a wind farm) and quantities are brought to the present assuming a 10% discount rate. We can thus calculate total expected coal generation in the base case, and total backup generation when a wind farm substitutes a coal plant.

We model wind variability by distributing the total energy generated by our representative wind farm in one year (1,900 GWh by assumption), according to the distribution of capacity factors of our average wind farm, and then recalculate total system operation and its cost. Last, we add backup fuel oil turbines until LOLP with a wind farm equals LOLP with a coal plant.[19]

C. *Investment*

Our simulations span 25 years. We use NEC (2007a) investment plan, which chooses both the mix of technologies (hydro, coal, liquefied natural gas (LNG) and fuel oil) and the timing of entry to minimize operating, investment and outage costs over time and is meant to simulate investment decisions of private generators. It can be shown that this corresponds to a dynamic market equilibrium with free entry.

To model the impact of substituting a wind farm for a coal plant on the optimal investment plan we assumed that the residual demand (i.e. after discounting the portion supplied by the wind plant) would be served by conventional plants. In this way, we calculated a new investment plan which we used to simulate Omsic.

V. RESULTS

Table VI shows our results. The first row reports the total levelized cost of coal and wind in $/MWh. The following rows decompose the levelized cost in its components. Panel (a) shows private costs. Panel (b) shows the cost of the externalities and efficient abatement.

Our main finding is reported in columns (1.1) and (1.2). The levelized cost of coal is $84/MWh. Of these, $23/MWh, or 27% of coal's total cost are caused by environmental externalities. By contrast, the cost of wind is $136/MWh---a difference of $52/MWh or 60% higher than coal. Thus, as long as air pollutants are abated, wind is more expensive than coal even if one adds the cost wrought by environmental externalities.

Why is wind less competitive than coal? Note that a kW of nominal capacity costs almost the same---$2,350 kW for wind against $2.300/kW for coal. Moreover, wind turbines neither use fuel, nor pollute the air, nor contribute to global warming. But, as the first row of panel (a) shows, wind loses all its advantage with low capacity factors. While the capacity factor of a typical coal plant exceeds 80%, our representative wind farm generates only 24% of its nominal capacity. Consequently, it must invest $120 per generated MWh, or roughly four times as much as a coal plant.

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[17] Until recently Omsic was used to dispatch units in Chile's SIC and operate reservoirs. See Appendix B in Galetovic and Muñoz (2009) for a detailed description of the model.

[18] More detail on applying dynamic programming in planning for hydrothermal systems is available in Pereira and Pinto (1991) and Power System Research Institute (2001).

[19] It has been pointed out to us that SIC's reservoirs could backup wind generation. However, this is more expensive than a turbine, because the opportunity cost of water during a drought is larger than the annual investment and operating costs of a gas turbine operating with fuel oil Nr. 6.

TABLE VI
THE LEVELIZED COST OF REPLACING
A 260 MW PC POWER PLANT WITH A WIND FARM
(IN \$/MWH)

	(1.1) Coal \$76[7]	(1.2) Wind 24%	(2.1) Coal \$50	(2.2) Wind 15%	(3.1) Coal \$120	(3.2) Wind 35%
Total	84	144	72	217	99	107
(a) Private costs						
Investment[1,2,3]	28	120	28	192	28	82
Fuel[4]	27	-	18	-	42	-
Operation	3	8	3	9	3	8
Transmission[5]	3	3	3	3	3	3
Backup[6]	-	13	-	13	-	13
Share	73%	100%	68%	100%	77%	100%
(b) Externalities and abatement costs						
Air pollutants	5	nil	5	nil	5	nil
CO_2	13	nil	13	nil	13	nil
Abatement	5	-	5	-	5	-
Share	27%	0%	32%	0%	23%	0%

Notes: (1) Present value of costs and generation calculated assuming an annual discount rate of 10% and a 25 year horizon. (2) We assume that a coal plant costs \$2,300/kW, including abatement equipment. The source is NEC (2009). To obtain the investment cost per kW without abatement equipment, we subtract the cost of abatement equipment, \$322/kW as reported in Table II, panel (b). (3) Wind turbines cost \$2,350/KW; see Table III. (4) Specific consumption of 0.34 tons of coal per MWh net. (5) Trunk transmission. Includes neither transmission investments needed to accommodate hourly wind volatility, nor the cost of connecting the wind farm to the trunk transmission system. (6) Investment in a 250 MW fuel oil backup turbine, operation cost and incremental operation cost of when a wind turbine substitutes for coal generation. (7) Source: NEC (2007a), which reports the cost of imported coal at a plant in Chile.

By contrast, panel (b) shows that backup is not responsible for wind's disadvantage. While 250 MW of turbines must be added to maintain LOLP, it adds only \$13/MWh to the levelized cost of wind, about 9% of the total.

Cost estimates are sensitive to load factors and the price of coal. Columns (2.1) and (2.2) show that if coal becomes cheap (\$ 50/ton) and the capacity factor is 15% (low but not that far from observed world averages) wind is almost three times more expensive than coal (\$72/MWh against \$217/MWh).

What would make wind competitive? Columns (3.1) and (3.2) show that even if the price of coal would increase to \$120/ton and, on the other hand, wind farms would reach capacity factors of 35%, wind would still cost slightly more than coal (\$99/MWh against \$107/MWh). Thus, wind would become competitive only if coal prices permanently rise to levels which, while observed sometimes during the last two or three years, are very high by historical standards; and capacity factors climb far above observed averages in most countries.

Alternatively, one might think that high carbon prices could make wind competitive. Nevertheless, according to our calculations, the marginal damage of CO_2, which we assume equal to \$13/tCO_2, would have to be equal to \$73/tCO_2 (\$268tC) to make coal and wind equally costly. This value is not only unlikely (it implies a marginal damage at the 98th percentile of the distribution reported in column (5) of Table V); at that point CO_2 abatement would likely become cost-effective. Hence, it seems unlikely that wind will become competitive in the near future, even if coal plants are made to pay for the externalities they cause.

REFERENCES

[1] M. Bolinger and B. Wiser, "Annual Report on U.S. Wind Power Installation, Cost and Performance Trends: 2007," Washington: U.S. Department of Energy, 2007.

[2] N. Boccard, "Capacity Factor of Wind Power Realized Values vs. Estimates", Energy Policy 37, 2679–2688, 2009.

[3] CDEC-SIC, Estadística de operaciones 2006, Santiago: Economic Load Dispatch Center for the Central Interconnected System, 2007.

[4] L. Cifuentes, C. de la Maza y F. Donoso, "Análisis técnico-económico de la aplicación de una norma de emisión para termoeléctricas". Mimeo, 2010.

[5] Corporación de Fomento de Chile, Evaluación del potencial de energía eólica en Chile, Corfo., 1993.

[6] Diaz-Guerra, B., Integración de la Generación Eólica en el Sistema Eléctrico Español", Power Point presentation, 2007.

[7] A. Galetovic, and C. Muñoz. "Estimating Deficit Probabilities With Price-responsive Demand in Contract-based Electricity Markets", Energy Policy 37, 560-569, 2009.

[8] Working Group III of the Intergovernmental Panel on Climate Change, IPCC 2005, IPCC Special Report on Carbon Dioxide Capture and Storage. New York: Cambridge University Press.

[9] J. Moreno, S. Mocarquer and H. Rudnick, "Generación eólica en Chile: análisis del entorno y perspectivas de desarrollo", Mimeo, Systep, 2007.

[10] N. Muller, and R. Mendelsohn, "Measuring the Damages of Air Pollution in the United States", Journal of Environmental Economics and Management 54 , 1-14, 2007.

[11] N. Muller, and R. Mendelsohn, "Efficient Pollution Regulation: Getting the Prices Right", American Economic Review 99 , 1714-1739, 2009.

[12] R. Muñoz, R. Garreaud, L. Gallardo, A. Cabello and B. Rosenbluth, "Mejoría del conocimiento del recurso eólico en el norte y centro del país". Santiago: Universidad de Chile, 2003.

[13] National Energy Commission, "Informe de precio de nudo, octubre 2003," Santiago: CNE, 2003.

[14] National Energy Commission." Informe de precio de nudo, octubre 2007," Santiago: CNE, 2007a.

[15] National Energy Commission (2007). "Prospección eólica en zonas de las regiones de Atacama, de Coquimbo y del Maule," Santiago: CNE, 2007b.

[16] National Energy Commission, "Informe de precio de nudo, octubre 2008," Santiago: CNE, 2008.

[17] National Energy Commission (April 2009). Informe de precio de nudo, abril 2009," Santiago: CNE, 2009.

[18] W. Nordhaus, "A Review of the Stern Review on the Economics of Climate Change," Journal of Economic Literature 45:606–782, 2007a

[19] W. Nordhaus, "Critical Assumptions in the Stern Review on Climate Change", Science 317, 201-202, 2007b.

[20] W. Nordhaus, A Question of Balance. Weighing the Options on Global Warming Policies. New Haven: Yale University Press, 2008.

[21] J. Oswald, M. Raine, H. Ashraf-Ball and E. Murphy, "UK Wind Farm Performance 2005, based on Ofgem ROC Data", 2006.

[22] M. Pavez, "Wind Energy Generation Feasibility on the Northern Interconnected System (SING)", Master's Thesis. Santiago: Pontificia Universidad Católica de Chile, 2008.

[23] M.V. Pereira, and L.M. Pinto, "Multi-stage Stochastic Optimization Applied to Energy Planning". Mathematical Programming 52, 359-375, 1991.

[24] Power System Research Institute, SDDP, "Methodology Manual, 2001".

[25] Ch. Santana., "Energía eólica en Chile: contexto y oportunidades", PowerPoint presentation, 2006.

[26] Supreme Decree No. 244, "Reglamento para medios de generación no convencionales y pequeños medios de generación establecidos en la Ley General de Servicios Eléctricos", Official Gazette of the Republic of Chile, January 17, 2006.

[27] R. Tol, “The Social Cost of Carbon,” Annual Review of Resource Economics 3, 419-443, 2011.
[28] R. Tol, “On the Uncertainty About the Total Economic Impact of Climate Change”, Environmental and Resource Economics 53, 97-116, 2012.
[29] Renewable Energy Policy Network for the 21st. Century, Renewables 2011 Global Status Report. Paris: Renewable Energy Policy Network for the 21st. Century, 2011
[30] U.S. Environmental Protection Agency (1998). “Compilation of Air Pollutant Emission Factors, AP-42, stationary point and area sources.” Washington: EPA, 1998.
[31] World Bank. Thermal Power: Guidelines for New Plants. Pollution Prevention and Abatement Handbook. Washington: The World Bank, 1998.

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