Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Wind, coal, and the cost of environmental externalities

Alexander Galetovic [a,*], Cristián M. Muñoz [b]

[a] Facultad de Ciencias Económicas y Empresariales, Universidad de los Andes, Santiago, Chile. Av. San Carlos de Apoquindo 2200, Las Condes, Santiago, Chile
[b] Departamento de Ingeniería Eléctrica, Pontificia Universidad Católica de Chile and AES Gener S.A., Rosario Norte 532, Piso 19, Las Condes, Chile

HIGHLIGHTS

- We compare the cost of electricity with coal and wind in Chile including externalities.
- Wind is competitive only with capacity factors around 35% and very high coal prices.
- Actual capacity factors of wind farms in Chile are about 20%.

ARTICLE INFO

Article history:
Received 29 April 2013
Accepted 27 July 2013

Key words:
Coal
Externalities
Wind power generation

ABSTRACT

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

The levelized cost of wind is \$144/MWh with capacity factor of 24%. This cost includes 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%.

Wind is competitive only with capacity factors around 35% and very high coal prices. Alternatively, a carbon price of \$73/tCO_2 (\$268/tc) would make coal and wind equally costly. But this value implies a marginal damage at the 98th percentile of the distribution deduced from Tol's (2011) estimates, rather far from the mean, \$16/tCO_2 (\$59/tc).

1. Introduction

Many hope that nonconventional renewable energy—wind, solar, small hydro, ocean and biomass—will stem the growth of generation with fossil fuels 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. We contribute 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 and the global externality wrought by CO_2.[2] Methodologically, we show how a comparison of levelized costs allows a complete cost-benefit assessment of long-term environmental and climate policies.[3]

To compare the cost of coal and wind we replace a 260 MW coal 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 of coal. Coal plants emit sulfur oxides (SO_x), nitrogen oxides (NO_x) and particulate matter (PM), which damage health, materials, visibility and crops. And they release CO_2, the main greenhouse gas, which causes global warming. We compute the levelized cost of coal with standard

* Corresponding author. Tel.: +56 226181259.
E-mail addresses: alexander@galetovic.cl (A. Galetovic), cmmunozm@uc.cl (C.M. Muñoz).

[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 system. Around 55% of installed capacity is hydroelectric.

[3] Levelized cost equals the per MW present value of the cost of building and operating a generating plant over an assumed economic life, converted to an annuity and expressed in terms of real dollars to remove the impact of inflation.

0301-4215/\$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.enpol.2013.07.140

estimates of emission factors and the marginal damage caused by each pollutant.

Second, wind capacity factors vary across locations and availability is volatile.[4] We estimate 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 cost of the thermal backups that maintain LOLP with higher wind generation.[5]

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. Thus we assume that conventional plats serve the residual load after wind generation (i.e. the load that remains to be served after subtracting wind generation), recalculate the optimal entry plan of conventional plants 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 megawatt hour generated with bituminous coal is \$84/MWh. The levelized cost varies with the price of coal between \$72/MWh with inexpensive coal at \$50/t up to \$99/MWh with coal at \$120/t.

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. 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.)

What would make wind competitive? Our estimates suggest that even if the price of coal rises to \$120/t and wind farms 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, a carbon price of \$73/tCO_2 (\$268/tC) would make coal and wind equally costly. But this value implies a marginal damage of CO_2 at the 98th percentile of the distribution deduced from Tol's (2011) estimates, rather far from the mean, \$16/tCO_2 (\$59 tC). Moreover, 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.

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. Section VI concludes.

[4] 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 8000 MW in 2007.

[5] 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: $LOLP = pr(load > net\ generation)$.

2. The environmental costs of coal

2.1. 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 which 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.[6] 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).[7,8] In addition, coal combustion releases greenhouse gases, mainly CO_2.

Table 1 reports maximum and minimum emission factors in kilograms 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 and lastly, panel (d) shows uncontrolled emissions of fuel oil No. 6 backup turbines.

Table 1 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.

2.2. 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.

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-

[6] In Chile the caloric content of bituminous coal is roughly 6350 kCal/kg. The caloric content of sub-bituminous coal is roughly 4000 kCal/kg.

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

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

Table 1
Emission factors for coal and oil (in kg/ton)[a,b,c].

	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	2385
Minimum	18.6	3.6	7.8	0.5	2165
(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	1959
Minimum	16.7	2.9	7.7	0.4	1894
Efficiency%	90[d]	80[e]	99[f]	99[f]	82
(d) Uncontrolled emissions, (fuel oil Nr 6)					
Maximum	22.3	6.4	0.8	0.9	3386

[a] We calculated emission factors for SO_x, NO_x and PM for coal with data contained in U.S. Environmental Protection Agency (1998), Tables 1.1–3; 1.1–6; 1.1–7 and 1.1–9.
[b] We calculated emission factors for fuel oil No. 6 with data contained in U.S. Environmental Protection Agency (1998), Tables 1.3–1; 1.3–4 and 1.3–12.
[c] We calculated emission factors for CO_2 with data contained in Working Group III (2005, table 8.1, p. 343), which reports CO_2 emissions per megawatt hour. To obtain emissions per ton of coal we assumed that 0.34 tons of coal generate 1 MWh. Note that CO_2 abatement is still experimental.
[d] Wet scrubbers (FGD): abatement efficiency > 90%.
[e] Selective Catalytic Reduction (SCR): abatement efficiency between 75% and 86%; we assumed 80%.
[f] Electrostatic precipitator (ESP): abatement efficiency = 99%.

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 2 shows 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.

Panel (a) in Table 3, which reproduces the first line in Table 2, 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 Mendelsohn (2007, p. 10), (Table 3) in the United States the marginal damage caused by a ton of NO_x is on average \$300, and \$3300 for a ton of $PM_{2.5}$. By contrast, Muller and Mendelsohn estimate that the marginal damage caused by SO_x emissions is \$1500 on average, between four and five times the damage estimated by Cifuentes et al. (2010) in Chile.

Table 2
Order statistics for marginal damages (in \$/ton).

	(1) SO_x	(2) NO_x	(3) $PM_{2.5}$	(4) C (Tol (2011))	(5) CO_2 (Tol (2011))
Mean	344	3085	20,714	59	16
SD	629	5642	38,244	77	21
CV	1.82	1.83	1.85	1.31	1.31
Min	1	11	71	−110	−30
10	1	15	93	−26	−7
25	9	83	529	4	1
Median	88	783	5117	44	12
75	419	3726	24,915	95	26
90	1048	9337	63,501	154	42
Max	9924	92,230	627,774	573	156

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).

Table 3
The marginal damage of pollutants and the cost of abatement.

	SO_x	NO_x	$PM_{2.5}$	CO_2
(a) \$/ton				
Marginal damage	344	3085	20,714	16
(b) Cost of abatement[a,b,c]				
\$/kW	172	83	70	–
\$/ton	336	251	451	71
(c) Marginal damages and cost of abatement in \$/MWh				
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				
\$/MWh	2.0	5.2	4.7	12.7

[a] We obtained costs of abating NO_x and SO_x from World Bank (1998, p. 423), in 1997 US dollars, and converted them to \$/2010 with CPI. Maximum values are used.
[b] We obtained costs of abating PM from industry information.
[c] We calculated the cost of abating one ton of CO_2 from Working Group III (2005, Table TS.10, p. 43). Mitigation costs include capture, transport and geological storage. We used the maximum value.

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 densely 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 3, panel (b) reports the cost of abatement per kilowatt of investment. Note that a coal plant costs about \$2000/kW without abatement equipment; installing that equipment for the three air pollutant would cost \$321/kW, increasing investment costs about

Please cite this article as: Galetovic, A., Muñoz, C.M., Wind, coal, and the cost of environmental externalities. Energy Policy (2013), http://dx.doi.org/10.1016/j.enpol.2013.07.140

16%.[9] 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 1900 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 of the same order for SO_x.

It is useful to compute damages per megawatt hour, and compare them with the levelized cost of electricity. To obtain damages per megawatt hour, compute the number of kilograms released into the atmosphere per megawatt hour generated. Because 0.34 t of coal generate 1 MWh, it follows that

$$(\text{kg/MWh}) = (0.34 \text{ tons}) \times (\text{emission factor})$$

is the total amount of the pollutant emitted when generating 1 MWh. The marginal damage per megawatt hour is

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

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

Panel (c) of Table 3 reports damages per megawatt hour. As a benchmark, consider the levelized cost of coal ignoring environmental externalities, which we estimate in $61/MWh (see Table 5 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 megawatt hour 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.

2.3. *The marginal damage of emissions: CO_2*

According to Tol (2011) as of 2010 there were 311 estimates of the marginal damage of a ton of carbon in 61 different studies.[10] Estimates vary a lot, despite that all are based on nine 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 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 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, ($157/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 stem from disagreement about the pure rate of time preference.[11]

To move ahead 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 2, 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.[12]

We obtained the cost of abating CO_2 in a coal power plant from the report by the IPCC Working Group III (2005). Abatement costs include capture, transport and geological storage and cost $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.

2.4. *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.

3. Wind

3.1. *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 (2007) argue that the cost per kilowatt of wind installed in the U.S. in 2007 varied from $1240 to $2600, with a mean of $1710. The average estimate from Bolinger and Wiser (2007), coming from projects proposed in 2006 (but at the time were still not executed), is that each kilowatt cost $1920.

In Chile, Moreno et al. (2007) estimated that each kilowatt of wind nominal capacity cost between $1100 and $1500. Santana (2006), on the other hand, gives a range between $1200 and $1800. Endesa, the largest Chilean generator, reported that its 18 MW Canela wind farm cost $350 million ($1928/kW).[13] Barrick,

[9] Note that abatement equipment uses energy and increases the plant's energy consumption from about 4% of gross energy to about 7%.

[10] 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 $\$59/3.67 = \$16.1$.

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

[12] 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.

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

Table 4
Cost of installing 1.65 MW Vestas V 82 turbines.
Source: Pavez (2008).

	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	1783	1793	1806
Construction	566	589.7	617.1
Total	2350	2383	2423

Table 5
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		

a mining company, reported that its Punta Colorada 20 MW wind farm cost $40 million ($2000/MW).[14]

Perhaps the most careful study of the cost of a wind farm in Chile is by Pavez (2008). Table 4 breaks down 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 $2350/kW. The cost per kilowatt increases as the size of the farm falls: the cost per kilowatt is $2383/kW for a 91 MW farm and $2422.90/kW for a 58 MW farm. We assume that each kilowatt of wind capacity costs $2350.

3.2. Capacity factors and wind variability

Because wind is volatile propellers rotate below their maximum capacity and factors of are comparatively low. [15] Boccard (2009) reported that between 2003 and 2007 the average capacity factor in Europe was just 21%. Oswald et al. (2006) reported the following capacity factors: United Kingdom 28.4%, Spain 26.6%, Denmark 24.1% and Germany 17.8%. Bolinger and Wiser (2007) reported 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 International Energy Association (2012), 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%.[16] 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-min intervals in eight different locations during more than a year (see Table 5).[17] With reported wind speeds we calculated how many megawatt hour a Vestas V66 2000/66 2 MW onshore turbine would have generated every 10 min at each site. Then we added generation over 1-h 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 (8760 h) in an “average” or “representative” wind farm.

Table 5 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 similar to observed capacity factors in other countries.

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% 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 11 AM they are uniformly below 10%.

4. Methodology

4.1. 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 260 MW coal plant generates about 1900 GWh (capacity factor $\approx$ 83%). To replace it with a wind farm one needs roughly

$$\frac{1900\ \text{GWh}}{(\text{wind capacity factor}) \times 8760\ \text{h}}$$

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

4.2. 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-

[14] See “Molinos de energía”, Special On-line Edition of El Mercurio, January 9, 2008.

[15] 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). Last, for wind speeds greater than the *cut-out* limit, the turbine is disconnected and power generation returns to zero.

[16] See Table 2 in the Executive Summary.

[17] Studies on Chile's wind potential include studies by Corporación de Fomento de Chile (1993) and Muñoz et al. (2003). Also see National Energy Commission (2007b).

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).[18,19] 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 wind substitutes for coal.

We model wind variability by distributing the total energy generated by our representative wind farm in one year (1900 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.[20]

4.3. Investment

Our simulations span 25 years. We use National Energy Commission (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 wind for coal on the optimal investment plan we assumed that the residual demand (i.e. after discounting energy 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.

5. Results

Table 6 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, reported in columns (1.1) and (1.2), is that the levelized cost of coal is $84/MWh. Of these, environmental externalities account for $23/MWh, or 27% of coal's total cost. 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 of environmental externalities.

Why is wind less competitive than coal? Note that a kilowatt of nominal capacity costs almost the same—$2350 kW for wind against $2300/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 megawatt hour, or roughly four times as much as a coal plant.

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 2 or 3 years, are very high by historical standards; and capacity factors climb far above observed averages in most countries.[21]

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 $13/t$CO_2$, would have to be equal to $73/t$CO_2$ ($268 tC) 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 5); 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 pay for the externalities they cause.

6. Conclusion

In this paper we have shown that efficient environmental policies that control emissions from coal plants are a no-brainer—social benefits outstrip costs by about an order of magnitude. Indeed abatement equipment is cheap and drastically reduces emissions of local pollutants, PM, NO_x and SO_x. On the other hand, policies that stimulate the installation of wind power, which are often justified in terms of their environmental benefits, are far less effective and quite expensive. The key driver of the cost of wind is the low capacity factor that a generator can achieve. This has often been overlooked because capacity factors assumed in planning have often been unrealistically high. By contrast, the cost of

[18] 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.

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

[20] 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 No. 6.

[21] Our estimate may be somewhat surprising. For example, U.S. Energy Information Administration (2013) reports a levelized cost between $89.5 and $118.3/MWh (average of $100.1/MWh) for a coal PC power plant; and a levelized cost between $73.5 and $99.8/MWh (mean value $86.6/MWh) for wind. Nevertheless, assumptions are different. EIA adds an additional charge equivalent to $15/ton of CO_2 in the form of a higher discount rate (roughly 10% in real terms after tax). Moreover, it assumes capacity factors between 30% and 39% (mean 34%) for wind farms and an after tax discount rate of 6.6%. By contrast, we assume a real before tax weighted average cost of capital (WACC) of 10% for both technologies and a capacity factor of 24% for wind.

Please cite this article as: Galetovic, A., Muñoz, C.M., Wind, coal, and the cost of environmental externalities. Energy Policy (2013), http://dx.doi.org/10.1016/j.enpol.2013.07.140

Table 6
The levelized cost of replacing a 260 MW coal plant with a wind farm (in $/MWh).

	(1.1) Coal $76[g]	(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[a,b,c]	28	120	28	192	28	82
Fuel[d]	27	–	18	–	42	–
Operation	3	8	3	9	3	8
Transmission[e]	3	3	3	3	3	3
Backup[f]	–	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%

[a] Present value of costs and generation calculated assuming an annual discount rate of 10% and a 25 year horizon.
[b] We assume that a coal plant costs $2300/kW, including abatement equipment. The source is National Energy Commission (2009). To obtain the investment cost per kilowatt without abatement equipment, we subtract the cost of abatement equipment, $322/kW as reported in Table 2, panel (b).
[c] Wind turbines cost $2350/KW; see Table 3.
[d] Specific consumption of 0.34 tons of coal per megawatt hour net.
[e] 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.
[f] Investment in a 250 MW fuel oil backup turbine, operation cost and incremental operation cost of when a wind turbine substitutes for coal generation.
[g] Source: National Energy Commission (2007a), which reports the cost of imported coal at a plant in Chile.

thermal backup for wind is actually not that significant as a share of total costs.

Of course, wind farms do not emit CO_2 but coal plants do. Nevertheless, the marginal damage from CO_2 must be significantly higher than the average of the values found in the literature in order for wind to be competitive with coal. And in such a case, CO_2 abatement might become cost-competitive. A corollary is that the various policies that have successfully spurred wind introduction around the world must have had very high costs associated with them.

Will technological progress eventually make wind competitive? On the one hand, many expect the cost of wind farms to decrease, the marginal damage caused by CO_2 to increase over time and coal prices have been high by historical standards during the last five years. On the other hand, technological progress should also reduce the cost of coal generation, and CO_2 capture may eventually become technically feasible and cost competitive. The jury is still out.

Acknowlegement

We gratefully acknowledge the financial support of AES Gener. We are fully responsible for the contents of this paper, which in no way commits AES Gener S.A. Galetovic gratefully acknowledges the hospitality of SCID at Stanford University and the financial support of Instituto Milenio P05-004-F *Sistemas complejos de Ingeniería*. Muñoz gratefully acknowledges the hospitality of PESD at Stanford University. We are very grateful for the suggestions of an anonymous referee.

References

Boccard, N., 2009. Capacity Factor of Wind Power: Realized Values vs. Estimates. Energy Policy 37, 2679–2688.
Bolinger, M., Wiser, B., 2007. Annual Report on U.S. Wind Power Installation, Cost and Performance Trends. U.S. Department of Energy, Washington.
Cifuentes, L., de la Maza, C., Donoso, F., 2010. Análisis técnico-económico de la aplicación de una norma de emisión para termoeléctricas. Mimeo.
Corporación de Fomento de Chile, 1993. Evaluación del potencial de energía eólica en Chile, Corfo.
Díaz-Guerra, B., 2007, Integración de ls generación eólica en el sistema eléctrico español. Power point presentation.
Galetovic, A., Muñoz, C., 2009. Estimating Deficit Probabilities With Price-responsive Demand in Contract-based Electricity Markets. Energy Policy 37, 560–569.
International Energy Association, 2012, IEA Wind 2011 Annual Report. Paris: IEA.
Moreno, J., Mocarquer, S., Rudnick, H. 2007. Generación eólica en Chile: análisis del entorno y perspectivas de desarrollo. Mimeo, Systep.
Muller, N., Mendelsohn, R., 2007. Measuring the Damages of Air Pollution in the United States. Journal of Environmental Economics and Management 54, 1–14.
Muller, N., Mendelsohn, R., 2009. Efficient Pollution Regulation: Getting the Prices Right. American Economic Review 99, 1714–1739.
Muñoz, R., Garreaud, R., Gallardo, L., Cabello, A., Rosenbluth, B., 2003. Mejoría del conocimiento del recurso eólico en el norte y centro del país. Universidad de Chile, Santiago.
National Energy Commission, 2007a. Informe de precio de nudo. CNE, Santiago. (October 2007).
National Energy Commission, 2007b. Prospección eólica en zonas de las regiones de Atacama, de Coquimbo y del Maule. CNE, Santiago.
National Energy Commission, 2009. Informe de precio de nudo. CNE, Santiago. (April 2009).
Nordhaus, W., 2007a. A Review of the Stern Review on the Economics of Climate Change. Journal of Economic Literature 45, 606–782.
Nordhaus, W., 2007b. Critical Assumptions in the Stern Review on Climate Change. Science 317, 201–202.
Nordhaus, W., 2008. A Question of Balance. Weighing the Options on Global Warming Policies. Yale University Press, New Haven.
Oswald, J., Raine, M., Ashraf-Ball, H., Murphy, E., 2006. UK Wind Farm Performance 2005, based on Ofgem ROC Data.
Pavez, M., 2008. Wind Energy Generation Feasibility on the Northern Interconnected System (SING). Master's Thesis. Santiago: Pontificia Universidad Católica de Chile.
Pereira, M.V., Pinto, L.M., 1991. Multi-stage Stochastic Optimization Applied to Energy Planning. Mathematical Programming 52, 359–375.
Power System Research Institute, 2001. SDDP. Methodology Manual.
Renewable Energy Policy Network for the 21st Century, 2011. Renewables 2011 Global Status Report. Paris.
Ch. Santana, 2006. Energía eólica en Chile: contexto y oportunidades. PowerPoint Presentation.
Tol, R., 2011. The Social Cost of Carbon. Annual Review of Resource Economics 3, 419–443.
Tol, R., 2012. On the uncertainty about the total economic impact of climate change. Environmental and Resource Economics 53, 97–116.
U. S. Energy Information Administration, 2013. Levelized Cost of New Generation Resources in the Annual Energy Outlook.
U.S. Environmental Protection Agency, 1998. Compilation of Air Pollutant Emission Factors, AP-42, stationary point and area sources. EPA, Washington.
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.
World Bank, 1998. Thermal Power: Guidelines for New Plants. Pollution Prevention and Abatement Handbook. The World Bank, Washington.

Please cite this article as: Galetovic, A., Muñoz, C.M., Wind, coal, and the cost of environmental externalities. Energy Policy (2013), http://dx.doi.org/10.1016/j.enpol.2013.07.140