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Assessment of wind energy potential in Chile: A project-based regional wind supply function approach

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ABSTRACT

Wind energy is now one of the fastest growing renewable energy sources in Chile, making it the second largest market for wind power in Latin America. This paper describes the evolution and the current state of wind power in Chile, presenting the location and performance of all wind farms in Chile. This article also aims to identify the locations of the most cost-effective wind energy potential to be developed in the near future, thus applying a project-based approach. This requires studying each individual wind farm under development or environmental evaluation. This means modeling 70 wind farm projects over the country summing 8510 MW. For each project hourly wind production profiles and histograms are developed, allowing the assessment of variability and spatial and temporal complementarity. The production of neighboring projects injecting their energy in the same transmission bus is aggregated, generating wind production profiles and histograms at transmission level. The Levelized Cost of Electricity of each project is used as a measure of economic feasibility and serves as input to produce wind supply functions for each region. This allows us to identify the most cost-effective wind energy zones for medium-term project development, a valuable input for transmission planners and the regulator.

1. Introduction

1.1. Wind energy development

Wind energy has been one of the fastest growing renewable energy sources over the world during the last decades [1,2]. At the beginning its development was facilitated by incentives and subsidies mainly in developed countries, but increasing thereafter with technology development, reductions in costs, improved access to funding [3], and sustained improvements in the assessment of wind energy potential.

Some developing countries, such as Chile, started later with the wind energy integration on power systems. The initial wind projects were developed with limited know-how, without long-term wind studies, without the aid of a national wind resource maps or any sort of national prospective of wind resources, leading to low-performance and high average energy costs.

1.2. Chile wind energy potency and incentives under the new energy law

In Chile, geographical characteristics, such as the long coastline, valleys and large mountain range, make the conditions for the movement of air masses, creating multiple sites with significant wind potential [4], estimated recently at nearly 40,000 MW potential available [5].

Likewise, the development of renewable energy has been proposed as a *government policy*. In 2013, the Chilean non-conventional renewable energy law (Law #20,698) incentivized renewable energy by imposing a 20% quota of renewable energy sales by 2025. Wind has been one of the main sources to meet this requirement. Besides this law, the government's *energy agenda* proposes to remove existing barriers to this type of energy, with a commitment of 45% of electricity capacity coming from non-conventional, renewable sources, which will be installed between 2014 and 2025 in the country [6].

In addition to its good wind energy potential, Chile is considered one of the most attractive countries to invest in alternative renewable energy in the region, because it is one of the main economies on the continent, occupying the first place in human development, GDP per capita, life expectancy, as well as political

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stability, absence of violence, access to capital and clear regulation [7]. Furthermore, higher local energy prices, which are often above USD 100/MWh, make a big share of the projects profitable, without the need of any source of subsidy. The Chilean government is trying to capitalize this advantage now through its energy policy. These features make Chile a very attractive country for the development of renewable projects.

The current political stage of the electrical system in Chile focuses on two processes linked to the transmission system, which allow improvements in the scenario for the incorporation of wind energy. These are a new integrated national market and the development of renewable energy zones:

- **Integrated national market:** It has been proposed to develop a long 500 kV transmission line connecting the two main Chilean electricity markets (as shown in Fig. 1.). The future interconnection between the northern system (SING) and the central-southern one (SIC) will improve access conditions for several new project developments and increase the energy prices for a big share of renewable projects (Alleviating congestion will increase both Spot and PPA prices) [8].
- **Renewable energy zones:** The second process is the study and possible development of new transmission for the connection of potential renewable energy zones. These are areas where a high energy potential has been properly assessed and real solutions are proposed to facilitate their development through connecting lines for shared use (mainly for wind, solar and mini-hydraulic developments).

The objective of this article is to identify potential wind projects and potential renewable energy zones as candidates to be integrated to the national electricity systems over the medium- term; a process that could take from a few months to years. Serving this purpose the rest of this paper is organized as follows. First, the state of operating wind farms is presented in Section 2. Section 3 introduces necessary notations and modeling concepts for estimating wind farm production. A deterministic technique is proposed, which is used to estimate the wind farm production in each potential site, considering air density variation and wind farm production losses. Section 4 describes wind power hourly profiles, analyzing the tendencies in each zone/region of the country. An economic assessment is also presented. Wind supply curves of main buses of the power system are analyzed in Section 5. The aggregate production from all wind farm projects is discussed in Section 6. The operating reserves required to deal with wind uncertainty and variability is discussed in Section 7. Finally,

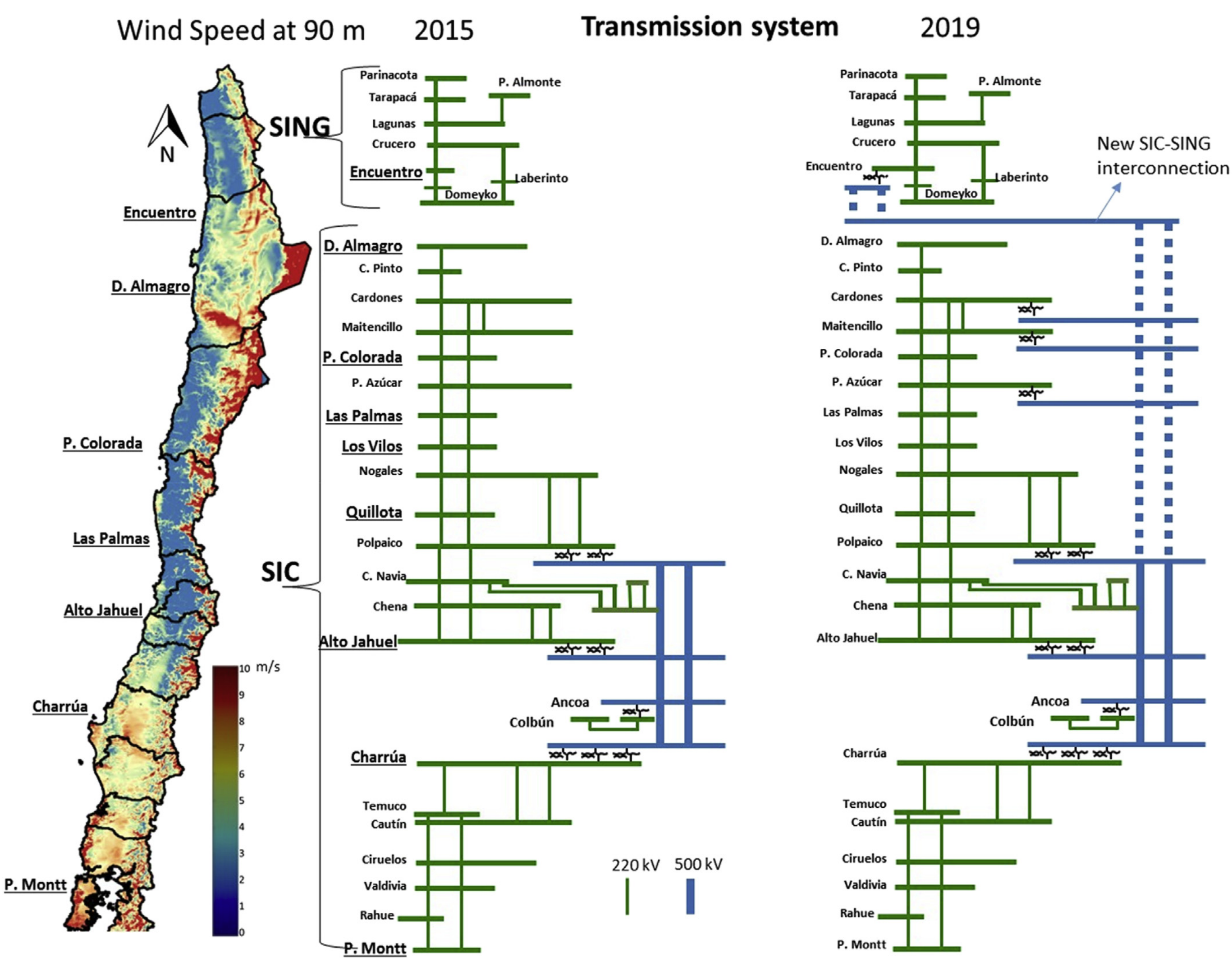


Fig. 1. Wind resource (Source: own elaboration using data from Ref. [9]) and expected evolution of the Chilean transmission network.

Table 1
Operating wind farms: technology, capacity and location.

Wind farms	Wind turbine model	System	Latitude	Longitude	Year	Capacity (MW)	Cumulative capacity (MW)
Canela I	Vestas V82 11 × 1.65 MW	SIC	−31.29	−71.63	2007	18.15	18
Lebu	Bonus/HEAG 7 unit	SIC	−31.30	−71.61	2009	6.5	25
Canela II	Acciona AW82 40 × 1.5 MW	SIC	−37.69	−73.65	2009	60	85
Tototal	Vestas V90 23 × 2 MW	SIC	−31.34	−71.60	2010	46	131
Monte redondo	Vestas V90 24 × 2 MW	SIC	−31.07	−71.64	2011	48	179
Punta colorada	Dewind D8.2 10 × 2 MW	SIC	−29.37	−71.05	2012	20	199
Ucuquer	Envision 4 × 1.8 MW	SIC	−34.04	−71.61	2013	7.2	206
Talinay oriente	Vestas V90 45 × 2 MW	SIC	−30.84	−71.58	2013	90	296
ValledelosVientos	Vestas V100 45 × 2 MW	SING	−22.53	−68.81	2014	90	386
Cuel	GoldWind GW87 22 × 15 MW	SIC	−37.60	−72.57	2014	33	419
El Arrayan	Siemens SWT-101 50 × 2.3 MW	SIC	−30.58	−71.70	2014	115	534
San Pedro	Gamesa G90 18 × 2 MW	SIC	−42.28	−73.94	2014	36	570
La Cebada	Vestas V100 21 × 1.8 MW	SIC	−31.03	−71.63	2014	37.8	608
El Pacifico	Vestas V100 36 × 2 MW	SIC	−31.05	−71.65	2014	72	680
Taltal	Vestas V112 33 × 3 MW	SIC	−25.09	−69.86	2014	99	779
Ucuquer Dos	Envisión EN110 2.1 MW	SIC	−34.04	−71.62	2014	10.8	789
Punta palmeras	Acciona AW116 15 × 3 MW	SIC	−31.23	−71.63	2014	45	834
Taninay poniente	Vestas V90 1.8 y 2 MW	SIC	−30.84	−71.58	2015	60	894

concluding remarks and future works are stated in Section 8.

2. Evolution of wind energy production in Chile

In Chile, in the early years wind turbines were not located in the best sites due to the lack of sufficient wind speed data and lack of studies of the wind resource across the country (national wind maps) making the development of cost-effective wind farms difficult. Moreover, it was necessary to minimize the additional costs of projects to develop a transmission line interconnecting the wind farm with the electric system. Under these conditions, profitable wind projects located close to transmission lines, were scarce. The first large scale wind project was installed at Canela, a coastal area in the IV region (northern-central Chile), in the year 2006. Since 2006, wind capacity has been steeply increasing, reaching a total of 894.45 MW installed in July 2015, as it is shown in Table 1. This makes Chile as the second largest market for wind turbine generators (WTGs) in South America and the Caribbean, behind the local giant, Brazil.

Larger wind turbines have been progressively been installed in the system. The individual capacity grew from 1.6 up to 3 MW in the latest wind farms. At the same time, sites selection has been improving, leading to wind farms with higher wind resource. The evolution of wind capacity, annual wind energy and capacity factor of operating wind farms are shown in Fig. 2. Actual capacity factors range between 16.73% in Canela I and 36.25% in San Pedro during 2014 [10,11]. However, the production of some wind farms are quite variable over the years. Vestas has been the main WTG supplier, and the models V100 of 1.8 MW or 2 MW were the most used technologies during this period [12].

The wind energy production in the two main Chilean power systems SING and SIC has been growing, from 0.1% in 2008 to 3.4% in 2015, as presented in Fig. 3.

The northern system SING has only one operating wind farm, supplying 1% of the demand. Here, energy prices are low due to the presence of several coal thermal plants. Conversely, in the central SIC there is a larger number of operating wind farms. 18 wind farms have been developed up to date. Wind production now accounts for 3% of the total energy of this system. In this case, despite wind projects difficulty to obtain PPAs, transmission constraints and limited cost-effective supply produced high spot prices, turning several wind farms more profitable.

An analysis of the seasonal variation in the production of the wind farms under operation is shown in Fig. 4. Since wind speeds varies significantly over the day and across seasons, energy production also changes accordingly. Coastal projects (identified with a (c)) show a higher seasonal variation in their production during the year, while valley (v) and mountain (m) projects show a more limited variation.

3. Wind speed data and methodology

In order to accurately evaluate the potential energy production of wind projects, it is first required to locate the wind farms in the optimal site. The technology for each wind farm is selected considering the hub height, average speed, and the effect of local air density in the power curve model of the WTGs. Finally, wind power output is corrected to reflect several sources of losses of the wind farms.

3.1. Available wind speed data in Chile

In developing countries, such as Chile, access to information concerning renewable resources is often scarce or unavailable (private data). This article is uses public available information whose source is a mesoscale complex model, which provides simulations of wind conditions in several grids using a mesoscale model WRF (Weather research and forecasting) in the whole Chilean territory [9]. The Wind Explorer of the Chilean Energy Ministry (*Explorador de energía* eólica) was selected because is the most accurate and comprehensive wind data source publically available now and it is the only source that provides estimates of hourly wind speed, wind direction, and air density at different hub heights across most regions of the country.[1]

3.2. Location of wind farms from the environmental evaluation system

Wind speed data series of a one-year period were obtained with an hourly time resolution throughout the year 2010 for each wind farm. The location of each wind project was obtained from the database of the environmental evaluation system (SEIA for its name in Spanish, "Servicio de Evaluación Ambiental"). The project

[1] Meteorological data are available only for a few sites, at low heights and over a limited time horizon. Such data along with on-site measurements are quite valuable for MCP applications but alone is not good enough for the estimation of energy production.

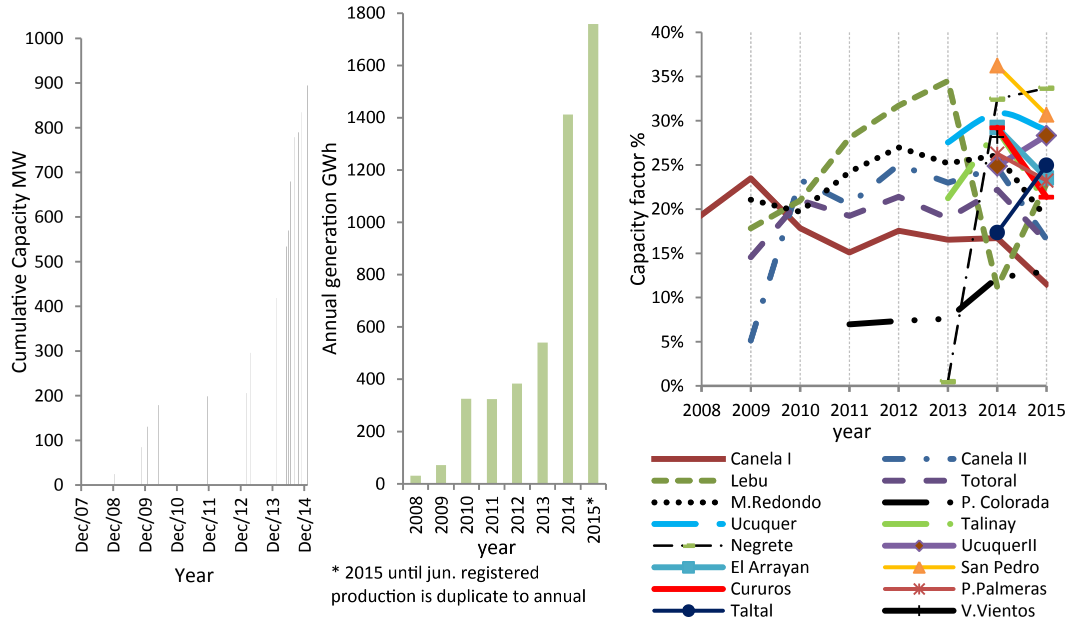


Fig. 2. Evolution of wind capacity (left), Annual wind energy (center), Historical capacity factor (right).

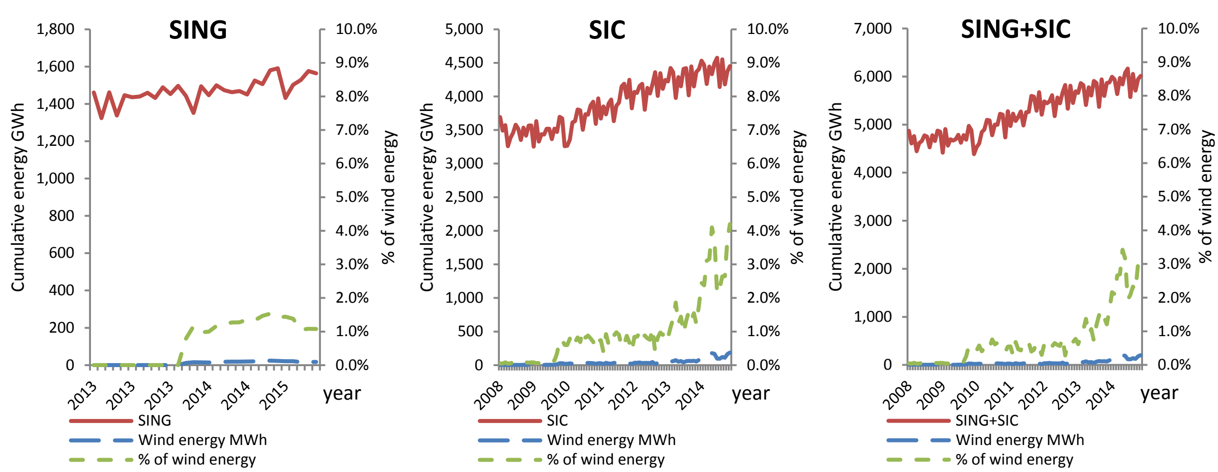


Fig. 3. Historical injections in the main Chilean system: SING, SIC and Total country.

portfolio is updated up to December 31st, 2014. The representative point for each wind farm was chosen close to the zone with higher power potential in each area.

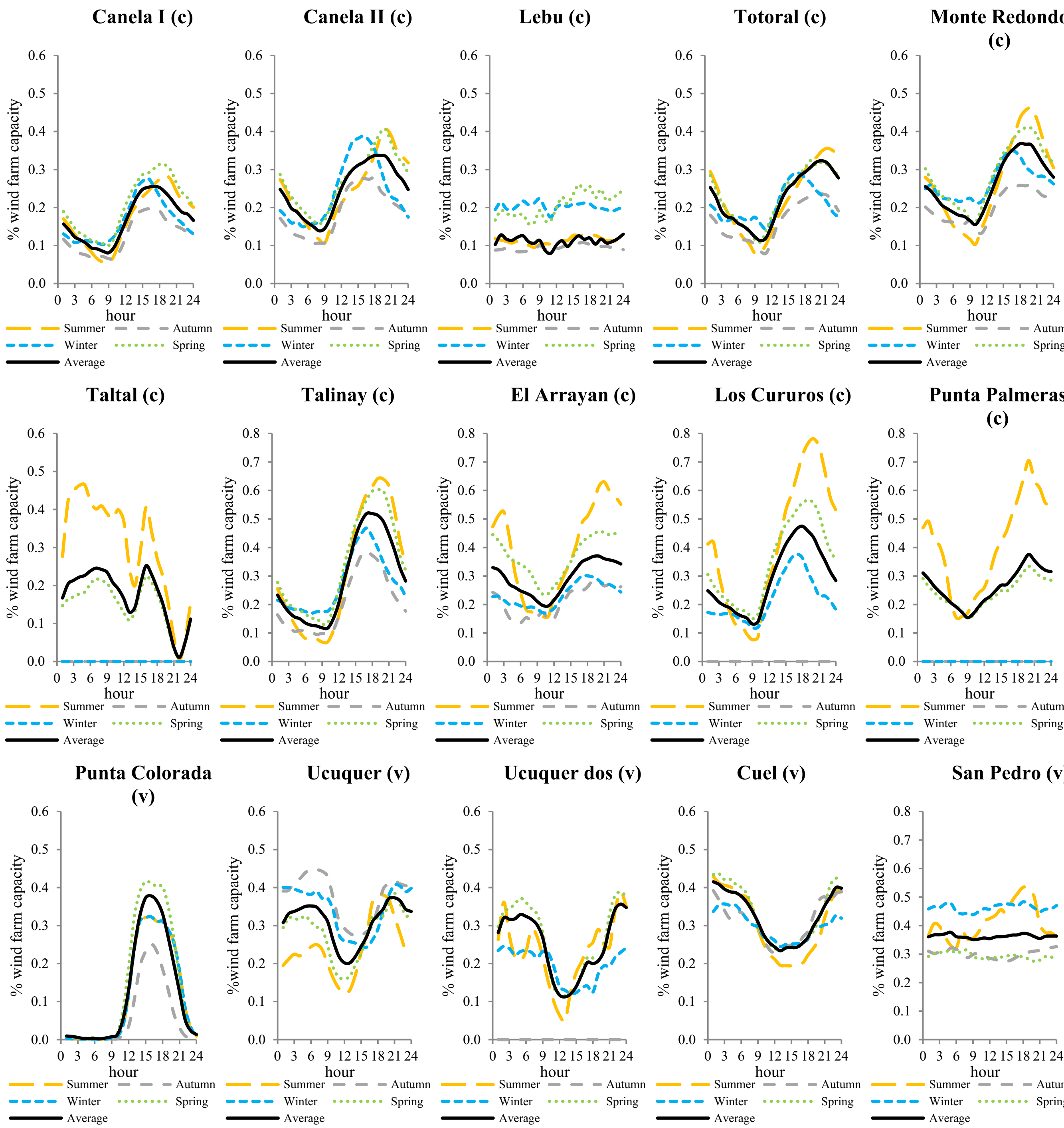
The database consists of the following: 70 wind farms of a wide range of capacities located across the north and center-south of Chile, the capacities varying between 9 and 500 MW. Currently 18 wind farms are operating with a total of 894.5 MW installed; nevertheless, these projects have environmental approval for up to 1206 MW, which could increase up to this value in the near term. Considering projects from all categories, i.e. those in the process of evaluation or having already achieved environmental approval (constructed or not), there is a total capacity of 8509.8 MW. This is detailed in Table 2.

3.3. *Effect of air density on the performance of a wind farm in coastline, valleys and mountain sites*

Air density is a local parameter that affects the modeling of the resource, because the kinetic energy of the wind is proportional to air density and wind speed. Furthermore, air density is a variable that depends on the atmospheric pressure and temperature in each site. While data on atmospheric pressure and air temperature are not available in sites, hourly air density is used, allowing the adjustment of the energy production of the WTGs.

The reference air density of 1.225 kg/m^3 used by WTG Manufacturers is obtained under standard conditions, i.e. temperature of 15 °C and 1013.3 mbar of atmospheric pressure [13,14]. This value of density is used in power curves by wind turbine manufacturers, but at lower air densities energy production would be reduced. Thus, it is possible to model this effect reducing energy production at lower air densities by decreasing the speed.

The relationship between wind speed and air density is defined in Eq (1), where v_{actual} is the actual wind speed measured on site in m/s, ρ_{actual} is the air density measured in the site and v_{corr} is the wind speed corrected by density ρ_{actual} to control for its departure from standard conditions.



(c): Coastal zone

(v): Valley zone

Fig. 4. Hourly wind profiles of operating wind farms in SIC. Source: CDEC SIC.

$$v_{corr} = v_{actual} \cdot \left(\frac{\rho_{actual}}{1.225}\right)^{1/3} \tag{1}$$

Most sites in Chile have air densities below the reference density (1.225 kg/m^3) as can be seen in Fig. 5. A), especially those sites in the mountain and high valleys which have air densities between 0.91 and 1.01 kg/m^3, while sites in the coastline and central valleys have air densities between 1.13 and 1.25 kg/m^3. At the same time, there are large air densities variations over the year as presented in Fig. 5. B) that shows the min, mean and max air densities of each site of the sample. For example, at the site “Chiloe 8, X” on the southern X region, the air density was 1.17 in March 1 at 5 p.m. (min) and 1.30 in July 16 at 7 a.m. (max). This is shown at the right site of side of Fig. 5. B). In order to factor in changes in air densities over the hours, each hour of the year is corrected according to the density measure.

Table 2
All wind farms: location, size and project name.

Wind farm	Capacity MW[b]	Latitude (°N)	Longitude (°E)	Wind farm	Capacity MW[b]	Latitude (°N)	Longitude (°E)
GranjaCalama	250.0	−22.44	−68.84	LasDichas	16	−33.306	−71.516
Calama	128.0	−22.50	−68.74	Ucuquer (7.2 + 10.8 MW)[c]	18	−34.045	−71.615
Calama A	108.0	−22.47	−68.78	SantaFe	204.6	−37.498	−72.529
Calama B	75.0	−22.47	−68.75	CampoLindo	145.2	−37.413	−72.494
Windpark	65.0	−22.46	−68.80	Mulchen	89.1	−37.679	−72.324
SierraGorda	168.0	−22.91	−69.02	BuenosAires	39.6	−37.531	−72.512
Tchamma	272.5	−22.50	−69.04	Mesamávida	103.2	−37.491	−72.472
Quillagua	100.0	−21.66	−69.50	LebuI (6.5 MW)	21.29	−37.686	−73.647
Taltal (99 MW)	99.0	−25.07	−69.84	LebuII	158	−37.702	−73.642
Loa	528.0	−21.46	−69.77	LebuIII	184	−37.738	−73.611
Ckani	240.0	−22.11	−68.58	LebuSur	108	−37.623	−73.667
ValledelosVientos (90 MW)	90.0	−22.49	−68.82	LasPeñas	9	−37.257	−73.426
MineraGaby	40.0	−23.46	−68.85	SanManuel	57.5	−37.507	−72.453
Sarco	240.0	−28.86	−71.46	Alena	107.5	−37.527	−72.561
CaboLeonesI	170.0	−28.94	−71.48	Raki	9	−37.741	−73.575
CaboLeonesII	204.0	−28.95	−71.49	Cuel (33 MW)	36.8	−37.513	−72.478
Chañaral	186.0	−28.87	−71.46	Kuref	61.2	−37.222	−73.505
PuntaSierra	108.0	−31.14	−71.65	Arauco	100	−37.218	−73.456
TalinayI	500.0	−30.83	−71.58	Chome	12	−36.775	−73.214
TalinayII (90 + 60 MW)[c]	500.0	−30.83	−71.68	AltosdeHualpen	20	−36.800	−73.170
SeñoradelRosario	84.0	−26.00	−70.27	LaFlor	30	−37.668	−72.599
PuntaPalmeras (45 MW)	66.0	−31.23	−71.64	PiñonBlanco	168.3	−37.827	−72.825
CanelaI (18.15 MW)	18.15	−31.29	−71.63	SanGabriel	201.3	−37.687	−72.525
CanelaII (60 MW)	60.0	−31.30	−71.63	Malleco	270	−38.024	−72.275
ElArrayan (115 MW)	115.0	−30.57	−71.70	Tolpán	306	−37.676	−72.619
LaCebada (37.8 MW)	37.8	−31.03	−71.63	Renaico	106	−37.718	−72.580
Quijote	26.0	−31.21	−71.62	Collipulli	48	−38.049	−72.280
LaGorgonia	76.0	−31.10	−71.65	Chiloé	100.8	−41.879	−73.989
ElPacifico (72 MW)	72.0	−31.05	−71.65	Aurora	192	−41.220	−73.144
LaCachina	66.0	−31.94	−71.51	Cateao	100	−42.902	−74.021
Totoral (46 MW)	46.0	−31.34	−71.61	Ancud	120	−41.908	−73.705
PuntaColorada (20 MW)	20.0	−29.37	−71.05	Pichihué	117.5	−42.388	−74.000
MonteRedondo (48 MW)	74.0	−31.07	−71.64	Llanquihue	74	−41.228	−73.214
LagunaVerde	19.5	−33.11	−71.72	SanPedro (36 MW)	36	−42.276	−73.924
Llayllay	56.0	−32.83	−71.00	AmpSanPedro	216	−42.305	−73.927
Subtotal operating wind farms capacity							894.3
Subtotal operating wind farms approval capacity							1326.0
Subtotal operating wind farms non constructed							7282.8
Total: 70 project in the portfolio, 18 operating wind farms in the system[a]							8509.8

[a] List of project registered up 31 December in 2014. 18 operating wind farms include stage part of project: Talinay II and Ucuquer.
[b] Operating wind farms with capacity equal or below to approval capacity. Source CDEC-SIC/CDEC-SING/SEIA.
[c] Talinay II was gathered wind farms: Talinay oriente, Talinay poniente. Ucuquer was gathered Ucuquer uno and Ucuquer dos.

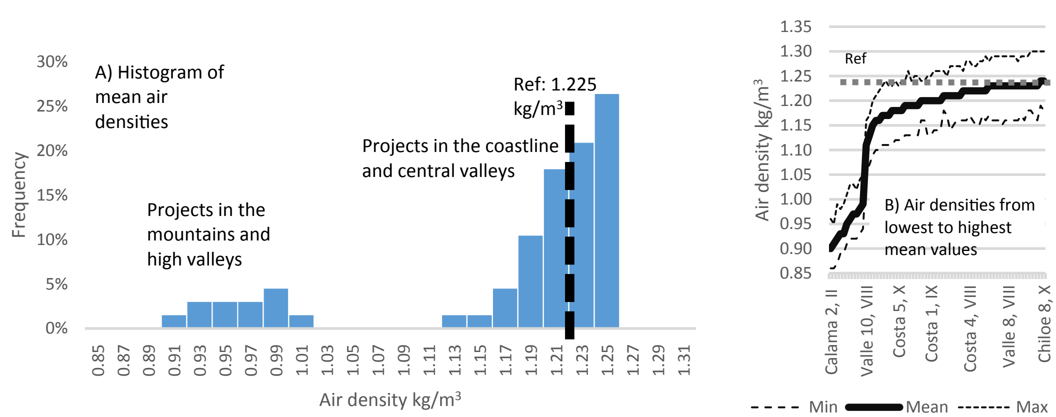


Fig. 5. Air densities at different sites. A) Histogram of mean air densities at each site and B) Minimum, mean and maximum air densities of each site (sorted from low to high values).

As a result of low air densities, most sites (75%) present a reduction in their corrected mean wind speed respect to their actual mean wind speed. The sites more affected by air density correction are those in Calama and Taltal where corrected wind speed goes down between 0.5 and 0.8 m/s because, as mentioned above, those projects are located in high altitude where air density is lower. On the other hand, only some projects in the south coast in Chiloe present a tiny increase in their corrected wind speed values between 0 and 0.1 m/s as is shown in Fig. 6.

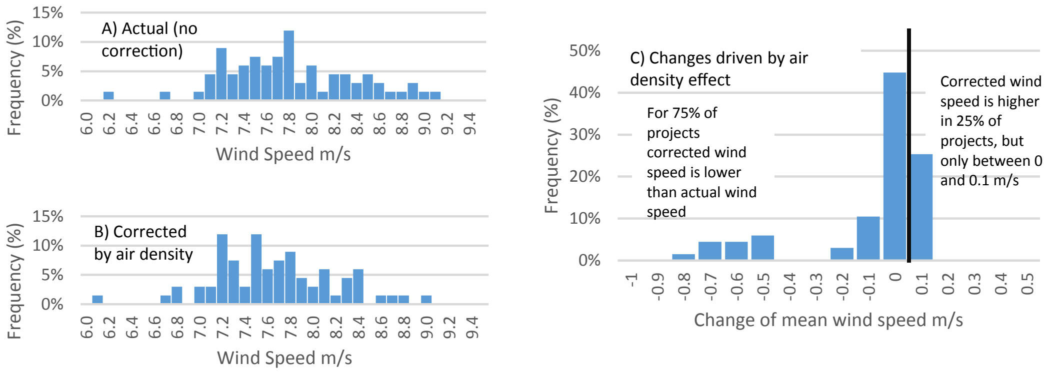


Fig. 6. Wind speeds at different sites. A) Histogram of actual mean wind speeds, B) Histogram of mean wind speeds corrected by air densities, and C) Histogram of changes of wind speeds (corrected speed − actual speed) due to air density effect.

3.4. Selection of wind turbines (WTGs)

The power generation of a wind turbine is strongly dependent on the technology used. Thus, adequate technology selection in line with the wind regime is fundamental.

The selection of wind turbines depends on the site and its wind regimes. It is essential that the wind resources and the topography are a accurately modeled for Wind class, hub height, sizing WTG, and the selection of the most cost-effective WTG [15,16]. Wind turbine power curves of all large scale projects in the Chilean system are presented in Fig. 7. According to these WTG power curves, the further to the left the better, as it increases production for the same level of wind; increasing capacity utilization and making the project more cost- effective.

Another essential point in the development of current wind projects is the fact, that several WTG shown in Fig. 7, were installed several years ago, with less-efficient technology than what is available now. In the last decades there has been great technology development for WTG targeted at low wind speed classes (wind classes I and II Class), allowing to produce energy in scenarios with low wind speeds. For modeled wind farms in the present study, three models are selected: 3 MW Nordex N117, 2 MW Vestas V100 and 1.8 MW Vestas V100, representing the power curves of most current technology widely available today [17].

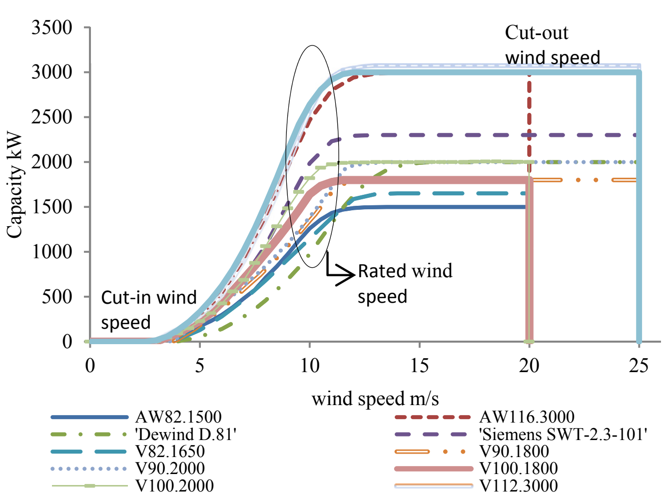


Fig. 7. Turbines of wind farms in Chile.

3.5. Wind turbine models, and wind generation estimation

Methodologies for the estimation of the production of a wind turbine generator (WTG), a wind farm, a wind development zone, a large region or a whole country are relatively similar, as they are all usually based on the methodology for the estimation of an individual WTG.

These methodologies often have two components, one estimating the resource (wind speed, air density, etc.) and another the effect of the technology. The wind speed is usually estimated through some sort of model or obtained from actual measurements, while the technology is modeled through static WTG power curves [15,17–20]. This is exactly the methodology followed for a specific WTG if the wind data is available at the same place and height of the WTG hub. Using time series of wind data (speed, air density, etc.) and a power curve, the production is accurately estimated.

Wind flow models, such as WindPro, OpenWind and others are often used to estimate wind beyond the spot where the measurements were performed. This is the case of most wind farms, where measuring only in a few spots, wind is estimated for all the WTGs.

Alternatively, mesoscale models can be used to obtain time series of wind speeds and using the power curve of a WTG wind power generation can be estimated. Since mesoscale models do not represent all the site details, their errors are higher than those from site models. This is the methodology selected for this paper [16,21–28].

Other analysis of regional potential, with no interest in estimating the specific production of a wind farm, estimate an approximate wind speed model. Once Weibull distribution parameters have been estimated, wind power density calculation is used to estimate wind power potential [29–34].

Another methodology for larger regions sometimes used is the multi-turbine power curve approach. This simplified methodology uses one WTG power curve, modifying it to represent the power curve of a whole area or region. This model aims incorporating some of the smoothing effect in both time and space as the area growth [35–41].

In this paper the selection of the methodology was based on the available information (wind speed data, air characteristics and frequency of measurements) and the outputs requirements: hourly wind power series, multi-point analysis, distance calculations, etc.

The power curves of three selected WTG (chosen as representatives ones) are modeled by four piecewise functions: using a polynomial regressions in the pseudo-lineal zone of the power curve (including the *constant efficient region* and the transition to the neighboring regions) and constant values on the other three regions. This means zero power for both low and extremely high wind speeds and nominal power for wind speeds between the rated and cut-off speed.

The generic wind power curves modeled is presented in Eq. (2), where P_{WTG} is the nominal WTG power, v_{in}, v_r and v_{out} are the cut-in speed, rated speed and cut-off wind speed respectively. The coefficients a_i from Eq. (2) are estimated using a polynomial regression that minimizes quadratic error with respect the original WTG power curve. The parameters are shown in Table 3.

$$P_{WTG}(v) = \begin{cases} 0 & 0 \le v \le v_{in} \\ \sum_{i=0}^{i=7} a_i \cdot v^i & v_{in} \le v \le v_r \\ P_n & v_r \le v \le v_{out} \\ 0 & v \ge v_{out} \end{cases} \tag{2}$$

Information on the technology selected at each project is obtained from the environmental evaluation documentation of the project (Servicio de Evaluación Ambiental - SEIA), where individual WTG power and hub height is identified. Older - lower efficiency - units are replaced by more current WTG models, in line with the industry common practice. Therefore, projects are modeled with 1.8, 2 or 3 MW units installed at a hub height of 78, 95 and 125 m each.

3.6. Estimations of wind farm production and wind farm losses

To model a wind farm, two types of methodologies are possible: modeling all the WTGs and calculating the aggregate generation [42,43], or modeling an individual WTG- as a representative of the wind farm [18,44]- and performing all necessary loss corrections. The latter is utilized in this study and consists of a simple two-step procedure:

Step 1: Modeling one isolated WTG without any source of losses in each wind farm. This WTG is located in one of the best spots of the site for maximum power production.
Step 2: Computing wind farm production using the WTG production, but correcting it by loss factor which considers all possible sources of wind farm losses and lower production of neighboring units due to wind speed differences among all the individual WTGs.

Therefore the estimation of the wind farms generation is obtained by first estimating the production of an average unit ($E_{individual-WT}$) by correcting the lossless production of the WTG at the best spot in the site $E_{max.unit}$, with a coefficient of “maximum over average effect” or (ε_{ma}), that accounts for wind speed differences among all the individual WTGs. After the production of an average unit has been estimated as $E_{max.unit}(1-\varepsilon_{ma})$, the classical losses factors (ε_{cl}) are applied, as presented in Eq. (3). This means, including the main sources of wind farm losses as Wake effect losses (ε_W) [37,45–50], electrical losses (ε_e) [37], over-statistical estimations (ε_s) [51], regular maintenance (ε_m) [52], as presented in Eq. (4).

$$E_{individual\ WT} = E_{max.unit}(1-\varepsilon_{ma})(1-\varepsilon_{cl}) \tag{3}$$

$$E_{individual\ WT} = E_{max.unit}(1-\varepsilon_W)(1-\varepsilon_e)(1-\varepsilon_s)(1-\varepsilon_m)(1-\varepsilon_{ma}) \tag{4}$$

Eq. (4) is applied in hourly power series to generate a more accurate wind farm model. The annual wind generation E_{annual} is obtained adding up the hourly power series for each wind farm over a year (see Table 4).

The capacity factor is defined as the quotient between wind energy production E_{annual} and the theoretical wind farm maximum production (when WTG is operated all the hours of the year at its nominal power); its expression is presented in Eq (5). If the capacity factor is high, means that the wind blows and the WTG is producing a large share of the time. This leads to wind farms more profitable for wind developers (ceteris paribus) [17], as the investment cost is being spread out over a larger amount of energy. The estimates of the capacity factor for all project are presented in Table 5.

$$Capacity\ factor_{Anual} = \frac{E_{annual}}{P_n \cdot 8760} \tag{5}$$

4. Hourly wind generation average profiles of projects injecting energy in buses

Chile presents a wide variety of wind regimes, due to its varied topography: coast, valleys and mountains, which provide wind profiles that show a predominance of production during the morning (wind projects in *Encuentro 220 kV* bus), flat regimes (in *Charrua and Puerto Montt 220 kV* buses), and regimes with predominance during the night (*Las Palmas, Punta Colorada 220 kV* buses, and other wind project located in the coastal area of Chile).

Hourly average generation profiles of wind farms are presented in Figs. 8–11. They are gathered by the main buses of the electric transmission system. Each bus (representing a whole region) shows a characteristic shape, where the influence of the same air mass affecting several wind farms' production is presented. Furthermore, wind projects, which inject energy in the same bus, often present similar topography. Thus, main buses are classified according to the kind of topography: coast, valley, and mountain buses. *Paposo, Punta Colorada*, and *Las Palmas 220 kV* present a coastal wind tendency (since the projects are located near the coast). The *Alto Jahuel, Charrua*, and *Puerto Montt 220 kV* buses have the topography of a valley, which has flat hourly profiles during the day. Finally, buses

Table 4
Wind farm losses.

Production losses	Expression	
Wake effect	ε_w	10.00%
Electrical losses	ε_e	2.50%
External losses	ε_s	1.00%
Regular maintenance	ε_m	1.00%
Classical losses subtotal	ε_{cl}	14.00%
Maximum over average effect	ε_{ma}	9.84%
Total production losses	ε_{total}	22.46%

Table 3
Polynomial coefficients of wind turbines generators.

Manufacturer	Model	P_n	a_7	a_6	a_5	a_4	a_3	a_2	a_1	a_0	v_{in} (m/s)	v_r (m/s)	v_{out} (m/s)
Vestas	V100 1800 kW	1800	0.02	−1.06	23.18	−271.59	1843.26	−7197.92	15003.46	−12903.01	2.5	12	20
Vestas	V100 2000 kW	2000	0.00	−0.02	−0.88	24.18	−240.93	1200.26	−2904.04	2690.56	3	12	20
Nodex	N117 3000 kW	3000	0.00	0.27	−9.24	149.68	−1310.70	6422.44	−16421.53	17022.68	2.5	12	25

Table 5
Capacity factors of wind farm projects.

Wind farm	Bus	Approval capacity MW	Capacity factor	Wind farm	Bus	Approval capacity MW	Capacity factor
Granja Calama	Encuentro 220 kV	250.0	33%	Las Dichas	Quillota 220 kV	16	19%
Calama	Encuentro 220 kV	128.0	36%	Ucuquer (7.2 + 10.8 MW)[a]	Alto Jahuel 220 kV	18	27%
Calama A	Encuentro 220 kV	108.0	32%	SantaFe	Charrua 220 kV	204.6	40%
Calama B	Encuentro 220 kV	75.0	31%	Campo Lindo	Charrua 220 kV	145.2	37%
Wind park	Encuentro 220 kV	65.0	34%	Mulchen	Charrua 220 kV	89.1	34%
Sierra Gorda	Encuentro 220 kV	168.0	36%	Buenos Aires	Charrua 220 kV	39.6	38%
Tchamma	Encuentro 220 kV	272.5	38%	Mesamávida	Charrua 220 kV	103.2	37%
Quillagua	Encuentro 220 kV	100.0	22%	Lebu I (6.5 MW)[a]	Charrua 220 kV	21.29	37%
Taltal (99 MW)[a]	Paposo 220 kV	99.0	46%	Lebu II	Charrua 220 kV	158	37%
Loa	Encuentro 220 kV	528.0	25%	Lebu III	Charrua 220 kV	184	33%
Ckani	Encuentro 220 kV	240.0	40%	Lebu Sur	Charrua 220 kV	108	42%
ValledelosVientos (90 MW)[a]	Encuentro 220 kV	90.0	33%	Las Peñas	Charrua 220 kV	9	34%
Minera Gaby	Encuentro 220 kV	40.0	21%	San Manuel	Charrua 220 kV	57.5	39%
Sarco	Punta Colorada 220 kV	240.0	42%	Alena	Charrua 220 kV	107.5	40%
Cabo Leones I	Punta Colorada 220 kV	170.0	30%	Raki	Charrua 220 kV	9	34%
Cabo Leones II	Punta Colorada 220 kV	204.0	26%	Cuel (33 MW)[a]	Charrua 220 kV	36.8	35%
Chañaral	Punta Colorada 220 kV	186.0	42%	Kuref	Charrua 220 kV	61.2	28%
Punta Sierra	Las Palmas 220 kV	108.0	43%	Arauco	Charrua 220 kV	100	34%
Talinay I	Las Palmas 220 kV	500.0	33%	Chome	Charrua 220 kV	12	29%
Talinay II (90 + 50 MW)[a]	Las Palmas 220 kV	500.0	41%	Altos de Hualpen	Charrua 220 kV	20	25%
Señora del Rosario	Diego de Almagro 220 kV	84.0	12%	LaFlor	Charrua 220 kV	30	40%
Punta Palmeras (45 MW)	Las Palmas 220 kV	66.0	37%	PiñonBlanco	Charrua 220 kV	168.3	37%
Canela I (18.15 MW)[a]	Las Palmas 220 kV	18.2	35%	SanGabriel	Charrua 220 kV	201.3	41%
Canela II (60 MW)[a]	Las Palmas 220 kV	60.0	36%	Malleco	Charrua 220 kV	270	33%
El Arrayan (115 MW)[a]	Las Palmas 220 kV	115.0	45%	Tolpán	Charrua 220 kV	306	39%
La Cebada (37.8 MW)[a]	Las Palmas 220 kV	37.8	36%	Renaico	Charrua 220 kV	106	39%
Quijote	Las Palmas 220 kV	26.0	29%	Collipulli	Puerto Montt 220 kV	48	29%
La Gorgonia	Las Palmas 220 kV	76.0	35%	Chiloé	Puerto Montt 220 kV	100.8	34%
El Pacifico (72 MW)[a]	Las Palmas 220 kV	72.0	39%	Aurora	Puerto Montt 220 kV	192	32%
La Cachina	Los Vilos 220 kV	66.0	28%	Cateao	Puerto Montt 220 kV	100	37%
Totoral (46 MW)[a]	Las Palmas 220 kV	46.0	30%	Ancud	Puerto Montt 220 kV	120	31%
Punta Colorada (20 MW)[a]	Punta Colorada 220 kV	36.0	12%	Pichihué	Puerto Montt 220 kV	117.5	45%
Monte Redondo (48 MW)[a]	Las Palmas 220 kV	74.0	31%	Llanquihue	Puerto Montt 220 kV	74	27%
LagunaVerde	Quillota 220 kV	19.5	45%	San Pedro (36 MW)[a]	Puerto Montt 220 kV	36	43%
Llayllay	Quillota 220 kV	56.0	16%	AmpSanPedro	Puerto Montt 220 kV	216	46%

[a] Operating wind farms.

with mountain wind are presented in *Encuentro 220 kV*, where there are varied wind profiles as well as production influenced by low air density values.

Analyzing hourly profiles, there are some very special cases which are useful for assessing complementary production. First, varied profiles are found in projects near the bus Encuentro 220 kV in the north of Chile. Its' profiles have different shapes and a high variability between valley and peak points, (diurnal or nighttime) according to the area where the wind farm is located (neighboring projects, 20–30 km apart, exhibit unusually high levels of complementarity between them). The second set of notable zones are located near the Charrua and Puerto Montt 220 kV buses, which present profiles with flat tendencies over several hours of the day. The third case is Las Palmas and Punta Colorada 220 kV which shows more wind generation in the evening (18:00 h); during this period, the spot price starts to peak, thus presenting similar production profiles for all the projects of this area.

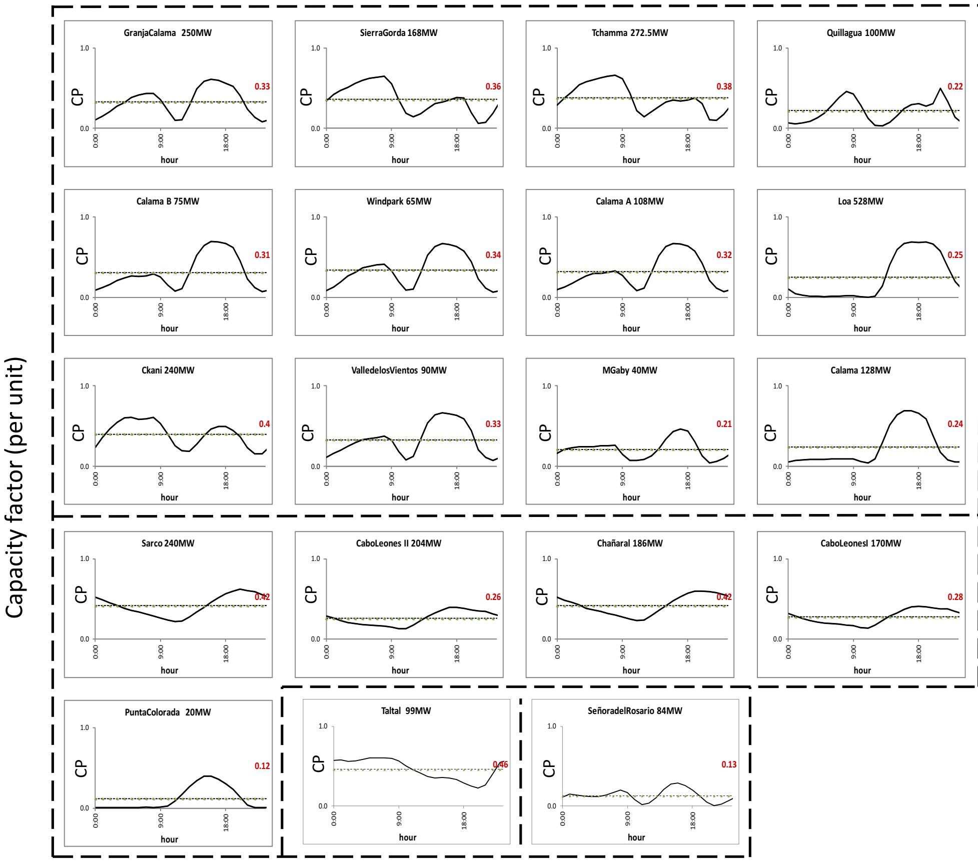
The characterization of hourly generation profiles in this study is useful in several other posterior studies related to wind penetration in the electric system such as estimation of reserve requirements, hourly ramp modeling, expansion transmission system studies, modeling hourly blocks, and building wind and hybrid project portfolios.

5. Assessment of wind farms potential: wind supply curve

5.1. Economic assessment

An economic evaluation is presented in this section. All proposed wind farms were assessed considering their investment costs and their expected operational factors. The economic assessment includes investment costs and the *O&M* (operation and maintenance) costs.

Investment costs are defined mainly by the cost of wind turbines, civil works and grid connection facilities, electric, metering and communication equipment, electricity infrastructure, amongst other factors. Over the last year local investment costs have varied from 1490 to 2471 USD/kW, with an average of around 2000 (2066).



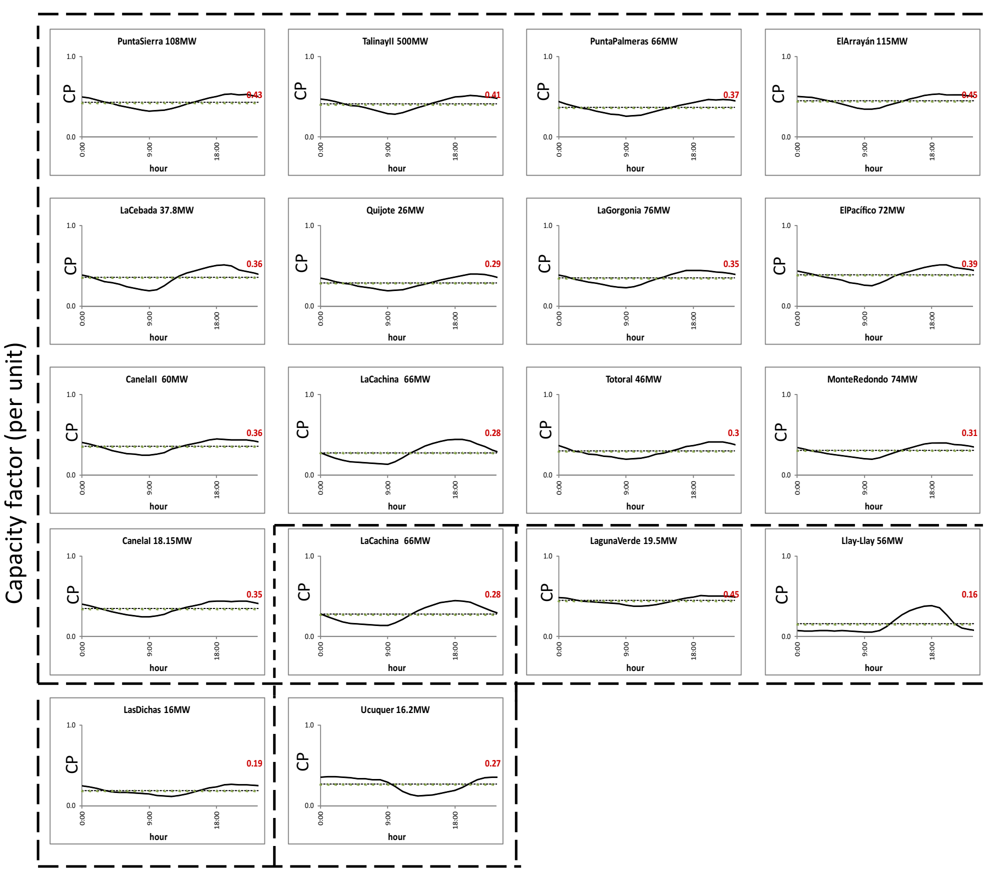
Encuentro 220kV	Capacity MW	Capacity factor
SierraGorda	168	36.4%
Tchamma	272.5	38.0%
GranjaCalama	250	33.5%
Calama	128	36.4%
Calama A	108	31.5%
Calama B	75	31.3%
Windpark	65	33.7%
Quillagua	100	21.9%
Loa	528.0	24.9%
Ckani	240.0	40.1%
ValledelosVientos Op (90 MW)	90.0	33.4%
MineraGaby	40.0	21.4%
Total Capacity	2064.5	

Paposo 220 kV	Capacity MW	Capacity factor
Taltal Op (99 MW)	99.0	45.6%

Diego de Almagro 220kV	Capacity MW	Capacity factor
SeñoradelRosario	84.0	12.0%

Punta Colorada 220kV	Capacity MW	Capacity factor
Sarco	240	41.8%
CaboLeonesI	170	30.5%
CaboLeonesII	204	26.0%
Chañaral	186	42.4%
PuntaColorada Op (20 MW)	36	12.1%
Total Capacity	836	

Fig. 8. Hourly wind profiles in northern buses.



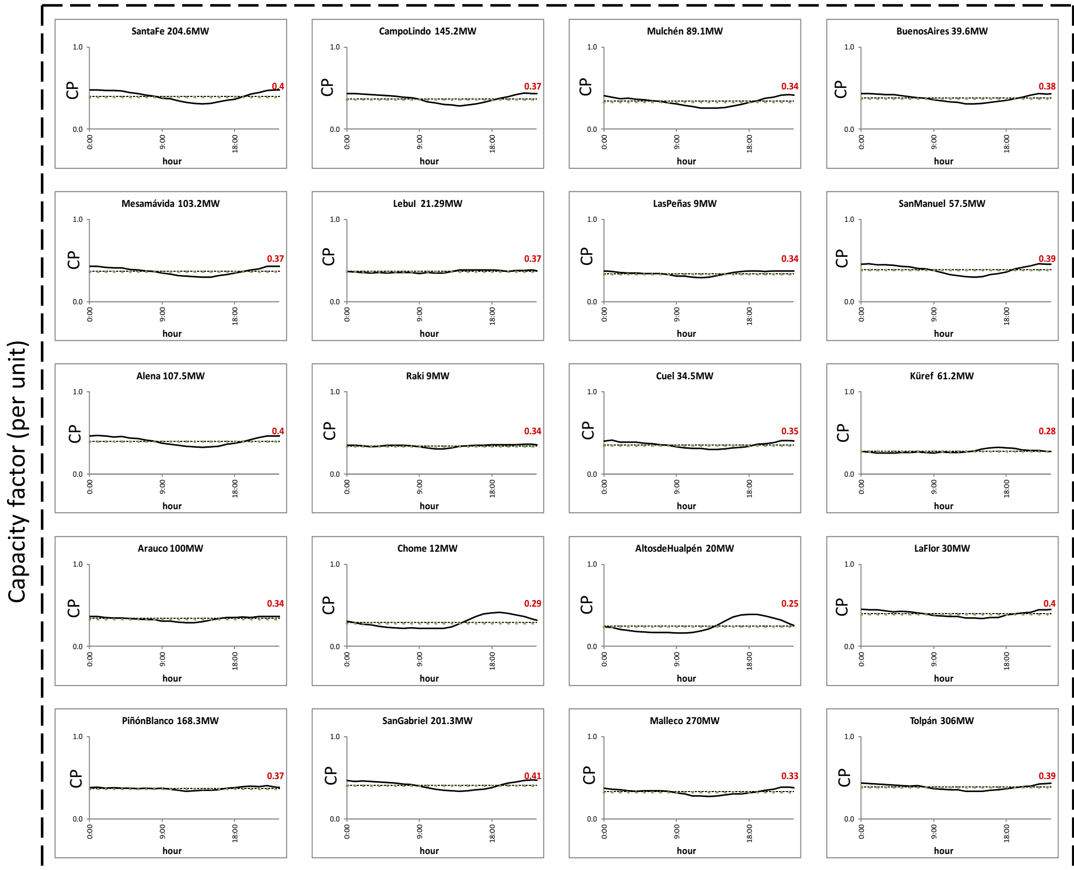
Las Palmas 220kV	Capacity MW	Capacity factor
PuntaSierra	108	43.1%
TalinayI	500	33.1%
TalinayII Op (90+60 MW)	500	41.3%
PuntaPalmeras (45 MW)	66	36.5%
CanelaI Op (18.15 MW)	18.15	35.4%
CanelaII Op (60 MW)	60	35.8%
ElArrayan Op (115 MW)	115	45.5%
LaCebada Op (37.6 MW)	37.8	35.7%
Quijote	26	29.4%
LaGorgonia	76	34.5%
ElPacifico Op (72 MW)	72	39.2%
Totoral Op (46 MW)	46	30.2%
MonteRedondo Op (48 MW)	74	30.6%
Total Capacity	1699.0	

Los Vilos 220kV	Capacity MW	Capacity factor
LaCachina	66.0	28.3%

Quillota 220kV	Capacity MW	Capacity factor
LagunaVerde	19.5	44.5%
Llaylay	56.0	15.9%
LasDichas	16	19.2%
Total Capacity	91.5	

Alto Jahuel 220kV	Capacity MW	Capacity factor
Ucuquer Op (18 MW)	18.0	26.6%

Fig. 9. Hourly wind profiles in buses: Las Palmas, Los Vilos, Quillota and Alto Jahuel 220 kV.



Charrua 220 kV	Capacity MW	Capacity factor
LebuI Op (6.5 MW)	21.29	36.5%
LebuII	158	37.1%
LebuIII	184	33.2%
LebuSur	108	42.3%
LasPeñas	9	34.4%
Kuref	61.2	27.8%
Arauco	100	33.5%
Chome	12	29.5%
AltosdeHualpen	20	25.2%
Raki	9	34.2%
SantaFe	204.6	40.4%
CampoLindo	145.2	37.3%
Mulchen	89.1	33.6%
BuenosAires	39.6	37.8%
Mesamávida	103.2	36.8%
SanManuel	57.5	39.2%
Alena	107.5	40.2%
Cuel Op (33 MW)	36.8	35.5%
LaFlor	30	39.9%
PiñonBlanco	168.3	37.2%
SanGabriel	201.3	41.0%
Malleco	270	32.8%
Tolpán	306	38.5%
Renaico	106	39.0%
Collipulli	48	28.8%
Total Capacity	2595.6	

Fig. 10. Hourly wind profiles in central-south bus.

O&M costs are considered to be between 20 and 30 USD/kW annually [53–58]. Since investment costs have been found to be quite variable over the space (from one project to the other) and over time (the same project in different points in time), this analysis has been developed considering a wide range of investment costs, using five scenarios with 2250, 2000, 1750, 1500 USD/kW and 1250 USD/kW, plus the case using investment costs actually reported by the project developer. The *O&M* cost has been assumed to be 25 USD/kW for all the projects analyzed.

The study uses a *discount rate* of 10%, which is widely used in energy economic evaluation in the Chilean industry as this is the default return by law in the transmission and distribution business, as well as the return used for generation plants in energy planning by the Chilean Energy Commission (Comisión Nacional de Energía - CNE). The assessment considers a *non-fuel variable costs* of 7.7 USD/MWh, in line with transmission cost studies developed by the CNE. The evaluation period is 20 years, which is a common lifespan for wind turbines.

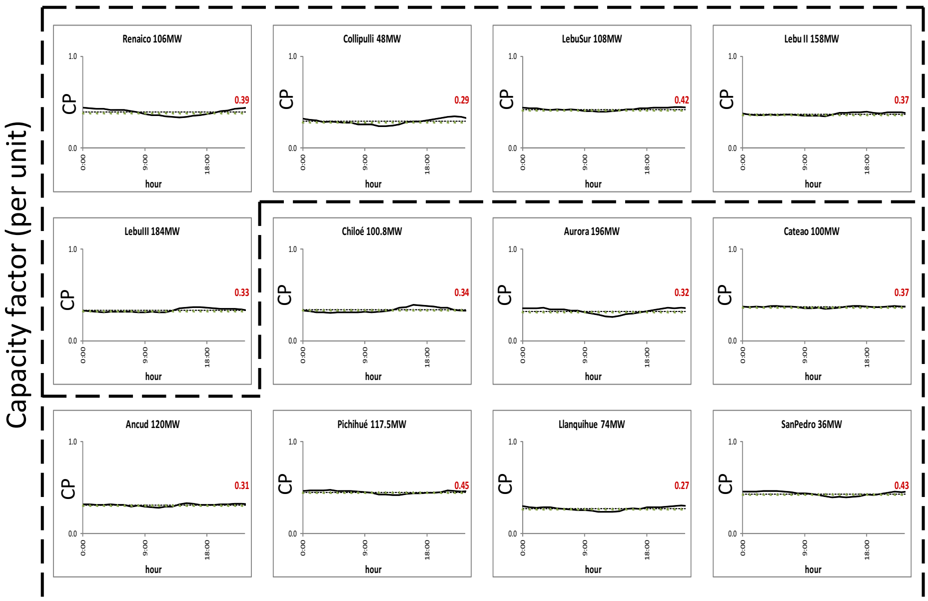
One of the most common and easy ways to understand the economic feasibility of a wind farm is through the study of the *levelized cost of electricity* (LCOE) [24,59–61]. LCOE is the ratio between the present value of total costs of the wind farm, and the present value of the energy generated by the plant during the evaluation period. The LCOE reflects the minimum price of the energy which would allow the project to recover its costs (including the return over capital). Eqs. (6)–(8) shows the calculation for LCOE.

$$\mathrm{LCOE} = FC\left[\frac{USD}{MWh}\right] + VC\left[\frac{USD}{MWh}\right] \tag{6}$$

$$\text{Fixed } costs: FC = \left(\frac{r_f \cdot C.I\left[\frac{USD}{kW}\right] + O\&M\left[\frac{USD}{kW}\right]}{fp \cdot hours_{year}[h]}\right) \tag{7}$$

$$\text{Capital } recovery\ factor: r_f = \frac{r}{\left(1 - \frac{1}{(1+r)^n}\right)} \tag{8}$$

LCOE is calculated using Eq. (6), which considers both fixed (*FC*) and variable costs (*VC*) of wind generation. Fixed costs (FC) have two components: the annualized capacity investment (*CI*) and the operation and maintenance cost (*O&M*) as is shown in Eq. (7). The capacity investment is annualized using a capital recovery factor (*rf*) that depends on the annual rate of discount (r) and the service life of the wind farm (n) (see Eq. (8)). Those factors are assumed to be $r = 10\%$ and $n = 20$ years respectively. Capacity investment and operation and maintenance costs are transformed into energy-based costs dividing them by the estimated annual production of the wind farm by unit of installed capacity which is estimated using their specific annual capacity factor (*fp*) and the number of hours in a year ($hours_{year}$), considered here as 8.760 h as shown in Eq. (7). Finally, as wind farms does not require any fuel, variable costs (*VC*) only includes non-fuel variable costs.



Puerto Montt 220 kV	Capacity MW	Capacity factor
Aurora	192	32.4%
Llanquihue	74	27.2%
Chiloé	100.8	33.6%
Cateao	100	36.9%
Ancud	120	31.0%
Pichihué	117.5	45.1%
SanPedro Op (36 MW)	36	43.4%
AmpSanPedro	216	45.6%
Total Capacity	956.3	

Charrua 220 kV	Capacity MW	Capacity factor
LebuI Op (6.5 MW)	21.29	36.5%
LebuII	158	37.1%
LebuIII	184	33.2%
LebuSur	108	42.3%
LasPeñas	9	34.4%
Kuref	61.2	27.8%
Arauco	100	33.5%
Chome	12	29.5%
AltosdeHualpen	20	25.2%
Raki	9	34.2%
SantaFe	204.6	40.4%
CampoLindo	145.2	37.3%
Mulchen	89.1	33.6%
BuenosAires	39.6	37.8%
Mesamávida	103.2	36.8%
SanManuel	57.5	39.2%
Alena	107.5	40.2%
Cuel Op (33 MW)	36.8	35.5%
LaFlor	30	39.9%
PiñonBlanco	168.3	37.2%
SanGabriel	201.3	41.0%
Malleco	270	32.8%
Tolpán	306	38.5%
Renaico	106	39.0%
Collipulli	48	28.8%
Total Capacity	2595.6	

Fig. 11. Hourly wind profiles in central-south buses.

5.2. Historical wind farm investment cost

The database of the environmental evaluation system (SEIA) is a data base that registers key data from all wind farms at project stage. Thus several technical and economical characteristics are presented here, including capacity, investment costs and important dates such as the presentation and approval date for the environmental evaluation. Using SEIA information, a statistical analysis of the investment costs was performed, aiming to identify potential economies of scales and trends.

Using the information presented by each project participant and classifying projects according to their presentation date (the date when the environmental study entered the system) the 70 projects were classified and gathered into groups by year.

This shows a wide variability in the investment cost each year; Fig. 12 presents a slight tendency towards economies of scales in the early years, but only for small projects (below 100 MW). Statistical analysis of historical information is shown in Fig. 13. Since 2008 there has been a slight decreasing tendency in the investment costs as time goes by. In line with this, the number of wind farm projects presented has been increasing from 2006 until 2014, because of public policies, high spot energy prices and the large wind potential still unexplored.

5.3. Wind supply curves in Chile

Wind capacity and wind energy along with its LCOE for all the projects is presented through regional and country-wide wind supply curves [59,62–65]. This representation arranges the projects from lowest to highest cost, forming an increasing curve in terms of supply cost that represents the amount of wind power (or wind capacity) economically feasible at each possible energy price. The wind supply curve provides a quick estimate of the regional or the national economic potential that could be developed in different scenarios [66].

Five wind supply curves are presented considering different

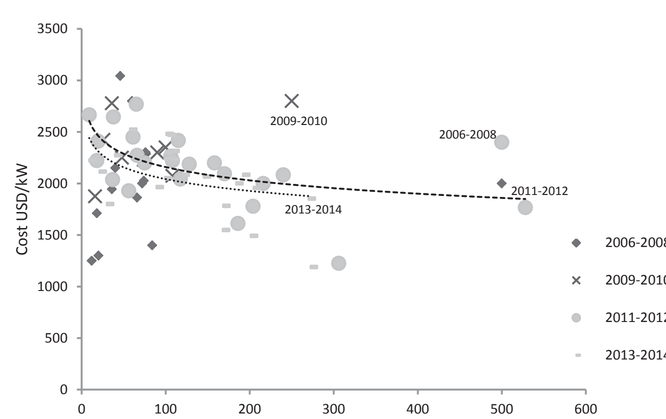


Fig. 12. Historical investment cost considering the capacity of each wind farm projects.

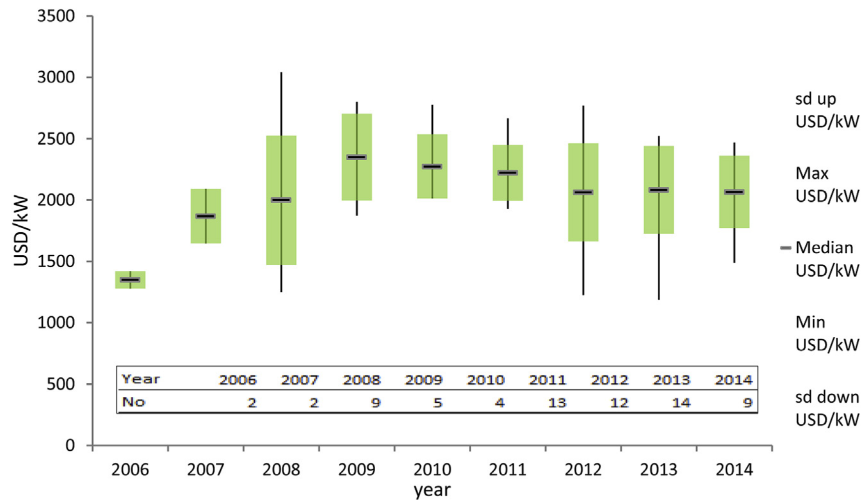


Fig. 13. Historical evolution of the investment cost of wind farm projects.

levels of investment costs in Fig. 14. In addition, a historical wind supply curve is presented, using the investment costs supplied at the time of environmental permit request.

The development of wind farms in Chile had been influenced by economic, political and social issues that led to very high spot energy prices, social opposition - freezing the development of conventional energy projects- and energy policy which favors renewables. This provides a clear scenario for the development of several wind farms during last few years, allowing the development of almost 830 MW, placing Chile in 2nd place within LATAM after the giant Brazil.

In an equilibrium-market scenario in Fig. 15, without the energy crisis effect, with a long-run spot energy price of 75 USD/MWh, the countrywide wind supply curve provides only 1578.3 MW. Alternatively, considering the global scenario of a sustained energy crisis, with spot prices close to 100 USD/MWh, wind farm potential projects could provide almost 5245.3 MW MW. One key issue limiting such large wind deployment is the fact that spot prices have been close to 100 USD/MWh for several years but not for twenty, as the LCOE computation assumes. Thus, the expected weighted average price is within the range of 80–85 USD/MWh, leading to a lower but still quite significant wind potential development. Transmission access and connection has consistently been a significant barrier to exploiting this potential.

6. Effect of aggregate generation of wind project in main buses of Chile

In order to analyze the effect of wind farms generation on the bulk electricity grid, this section presents the total power injections into the main transmission buses of the system. Production of all neighboring wind farms injecting their production into the same bus are aggregated. This produces different levels of spatial smoothing effect leading to “better behaved” wind productions. These average hourly wind farm generation profiles and histograms of aggregate generation are referenced to the each injection bus in the map of Chile in Fig. 16.

These histograms of bus generation present interesting shapes, corresponding to the probability distribution of aggregated wind production. The northern bus *Encuentro 220 kV* has a flat probability distribution at different levels of power production with few hours with maximum generation, requiring limited amounts reserves. This means that changes in wind production from neighboring wind projects tend to cancel out, smoothing the overall total

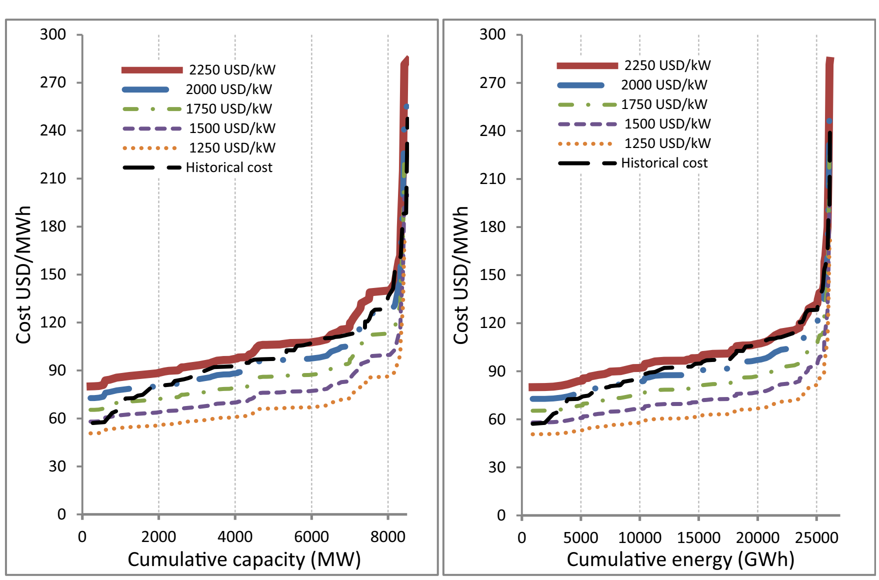
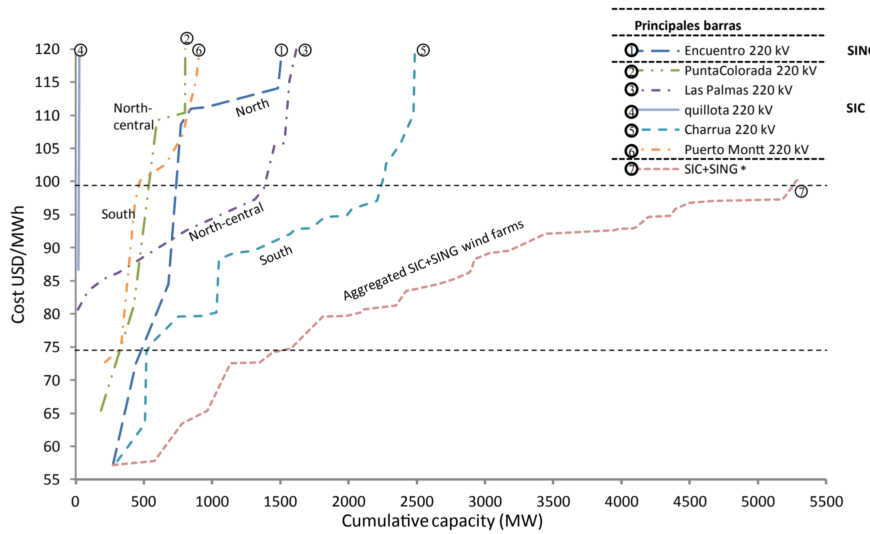


Fig. 14. Wind supply capacity and energy curves in five scenarios of investment cost.



*Historical investment cost USD/kW
** it also includes northern buses *Paposo* and *Diego de Almagro*, north-central bus *Los Vilos*, and central bus *Alto Jahuel*, which are not presented in the figure because they only host one project each

Fig. 15. Wind supply curves in main buses of the Chilean power system.

production.

The buses in the central-north *Diego de almagro, Punta colorada* and *Quillota 220 kV* present many hours with nil generation and others with maximum generation because the neighboring projects have a higher correlation in their production. Projects here also have a bit lower capacity factors.

The buses *Paposo, Alto jahuel* and *Puerto Montt 220 kV* present a distribution with many hours with maximum capacity and fewer hours with nil generation, as well as wind farms with high capacity factors and hourly profiles with high correlation. Finally, *Las Palmas and Charrua 220 kV* have a production distribution with two peaks, a large number of hours with nil or maximum generation and lower levels of energy in intermediate capacity; these shapes of wind production probability distribution are present in buses with a large quantity of projects, high capacity factors and medium or high correlation among them.

7. The need for additional operating reserves

Operating reserves help protecting against the inherent variability and uncertainty of supply and demand found in power system operations across different time scales [67,68].

The increase of wind power penetration requires providing adequate and sufficient reserves to the system, compensating for the additional intermittency and uncertainty introduced by wind generation. However, those reserve requirements cannot be quantified here, since they do not depend only on the variability of wind energy generation, but also on the variability of other sources of supply (such as solar farms, run of the river hydro plants, etc.), variability of demand, power system operational practices and market mechanisms, etc. For an international comparison of operating reserves requirements driven by wind power integration see Milligan et al [67].

While in central and southern Chile reserves are mostly driven by "traditional" demand and supply changes, reserves at the north of Chile are highly driven by contingencies in large combined cycle plants and sudden disconnection of large mining customers. This article is focused only on wind generation and therefore it cannot be used to compute reserve requirements. However, following [69–72], some examples of wind generation ramps can be provided.

It can be seen in the Northern Calama zone that as installed capacity of wind power increases (see Fig. 17.) from 75 MW to 1937 MW (from 1 to 12 projects), wind production deviations from one period to the next increased considerably, evolving from tens of MWs to several hundreds of MWs. This is shown to provide a notion of the extra ramping required when introducing additional wind capacity, but since this figure is built over the same databank used in this paper it contains only 1-h step changes in production. However, for the purpose of quantifying reserves, more frequent wind production estimates are required. This usually means assessing 1-min, 5-min, 10-min, 30-min and/or 1-h step changes in production to match different types of reserves (operating in different time scales) [73–76].

Operating reserve costs at high levels of wind penetration can be significant, burdening generation projects or customers' bills, depending on the cost allocation rules of the system. According the new Chilean electricity law those costs are going to be passed onto the consumers, thus not affecting the profitability of wind projects (not directly). Moreover, the Chilean system has some particularities that allow for the provision of reserves at lower costs. These are the following: 1) Chile has a large installed capacity of dam hydroelectric power which can provide inexpensive reserves, 2) Chile has an enormous potential of solar resource that complement with wind resources during the night, reducing reserve needs and 3) the new transmission law (still under discussion in the congress) promote a robust transmission network which allows operational reserves to travel further away over the system and reduces the costs of reserves.

8. Conclusion and discussion

Chile provides very low levels of risk for renewable energy projects, thus facilitating access to capital and leading to lower annualized investment costs. Beyond these economic and political factors, Chile presents a high wind potential due to its lengthy territory (6435 km) and coastline (4270 km), as well as its diverse topography. However, a large share of this potential is not close enough to transmission or it is limited by transmission capacity constraints. New transmission expansions and regulatory changes

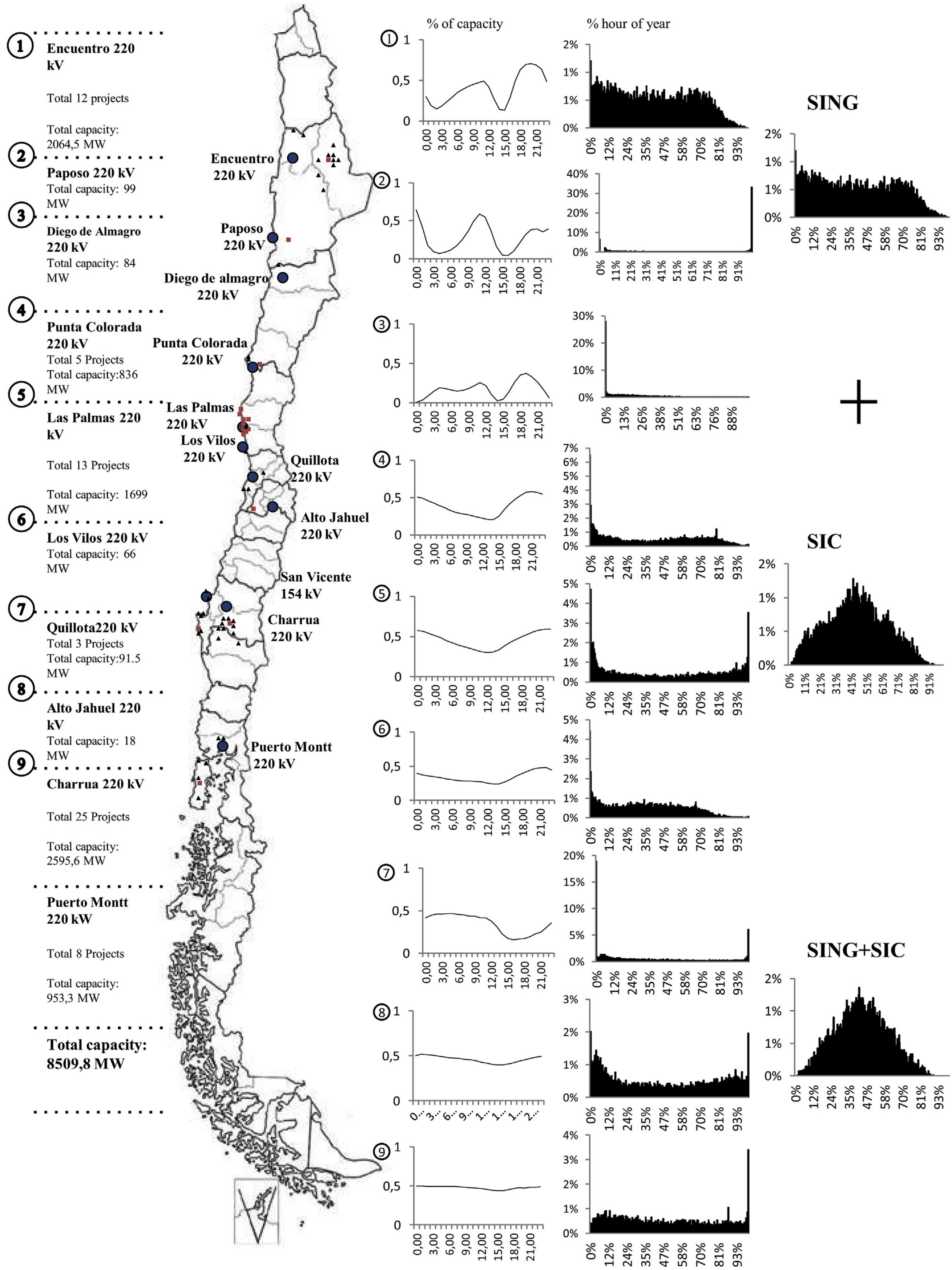


Fig. 16. Characterization wind farm buses: profiles and histograms of aggregate generation.

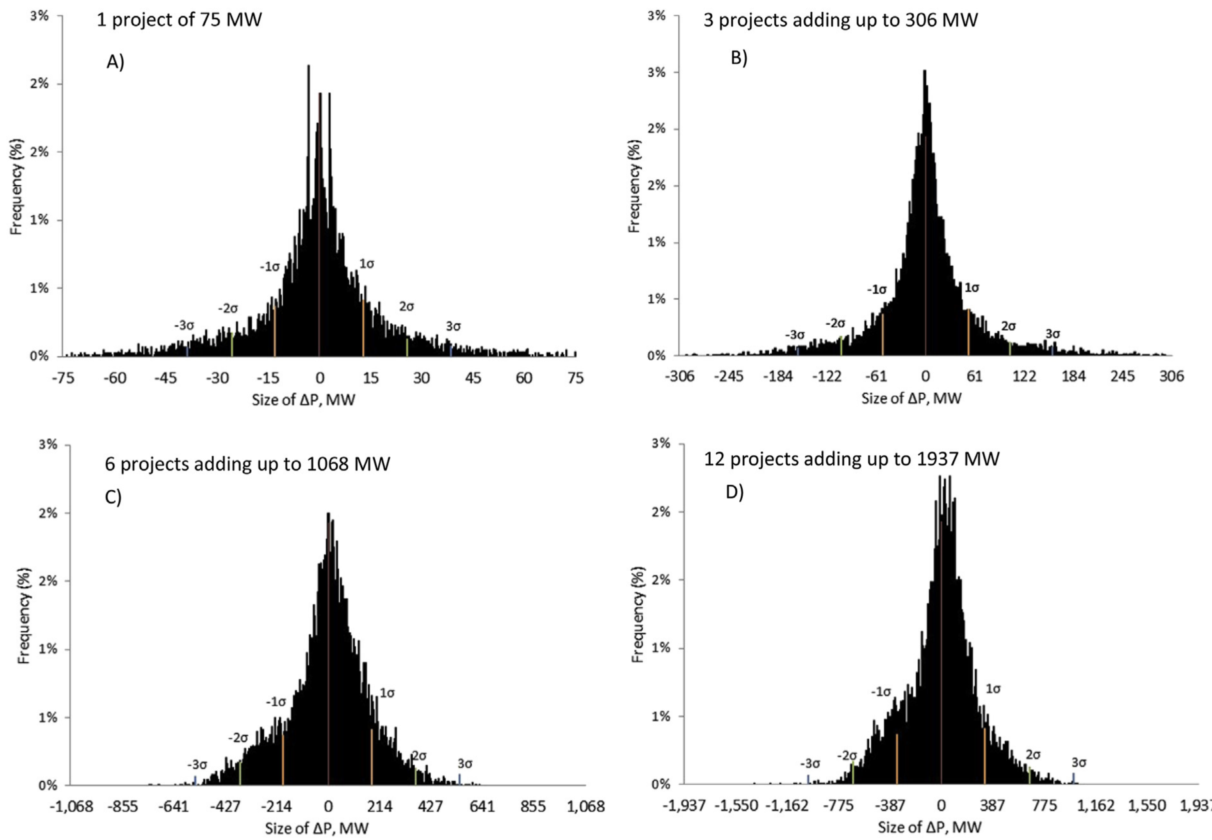


Fig. 17. Distribution of hourly step changes of aggregate wind production in the Calama Region: a) Production of 1 windfarm (75 MW), b) Production of 3 windfarms (306 MW), c) Production of 6 windfarms (1068 MW), and d) Production of 12 windfarm (1937 MW).

are altering this landscape, producing interest in the study of potential wind supply in the near future.

This paper studies the production of 70 potential wind projects that sum up 8509.8 MW (26 TWh/yr) including the operational and projected wind farms. It provides the most accurate prediction of the technologically feasible potential to be integrated in the near future.

The modeling of each wind farm considers the capacity of each wind turbine, hub height, local air density, correction factor to account for multiple sources of losses and its connection to the main transmission system, being the most complete national study on wind energy mid-term potential.

The simulation of hourly profiles over a year for all projects and the aggregation of the production profiles into the main transmission buses of the national electrical system produces aggregate wind production profiles. These profiles are a very valuable input to transmission planners, system operators and the regulator, as they incorporate the benefits of spatial and temporal aggregation and complementarity (including production correlation).

Typical wind production patterns: The typical characteristic of wind farm profiles have been related to the topography of zones such as coastal, valleys and mountains. The northern buses, *Paposo, Punta Colorada* and *Las Palmas 220 kV*, face coastal winds, characterized by a higher generation during the evening. The central-south buses of *Alto Jahuel, Charrua* and *Puerto Montt 220 kV* have a topography of valleys, with relatively flat winds during the day. Wind farms located in Northern Chile, in *Los Andes mountains*, near bus *Encuentro 220 kV*, show varied wind profiles. Air density here is quite low, reducing wind production considerably.

Energy production and potential: Capacity factors were estimated for all actual and potential wind farms in Chile, their values varied from 12% in *Punta Colorada* up to 45.6% in *Taltal* and *San Pedro*. With an average of 33.9%, a median of 34.5% and with only 5% of the projects showing very low energy production (below 20%). Central Chile, near the main load center (Santiago) is found to have very limited wind potential, of only a couple of small projects, but wind farms in the north and south of the country have a very large wind potential.

The modeling of each wind farm considers the capacity of each wind turbine, hub height, local air density, wind speed, correction factor of multiple sources of losses, and its connection to the main transmission system, which is the most complete national study on wind energy mid-term potential.

Wind supply curves and cost-effective potential: Using LCOE we provide a measure of cost-effectiveness to each wind farm, and sorting them according to this measure, we are able to produce a national wind supply curve. In addition, wind supply curves are constructed at each main transmission bus of the systems, allowing to produce regional wind supply curves and helping the identification of the locations with the most cost-effective potential across the country. Reviewing the case where the spot price was near 75 USD/MWh, it is only possible to develop 1578.3 MW of wind projects, producing nearly 5644, 5 GWh per year. The average capacity factor of these projects (the most cost-effective in the country) is 40.2%. This can be compared to the statistics of the projects actually developed, which produced less than a third of that energy but with half the installed capacity.

The wind projects developed up to December 2014 amount to 834.5 MW of installed capacity, but produced only 1412 GWh, with an average capacity factor of 24.79%. Projects' capacity factors started below 20% in 2008, but are growing quite quickly, with an average of 0.8% per year, due to a better knowledge of the resource, acquisition of know-how on project development, technology development, etc. However, access to transmission and transmission congestion costs are still a pending issue, leading to the development of less cost effective projects. The current transmission expansion on 500 KV across the country will relax this constraint.

With current energy prices, bordering 100 USD/MWh, the most cost effective wind energy production is in the south. At these prices it is possible to develop more than 5245.3 MW, producing more than 17843.3 GWh/yr, with a 37.9% average capacity factor and 25.2% for the worst performing project. In practice, several projects have been developed with the aim of even lower capacity factors, however, most of them have been able to secure PPAs with even higher prices and/or have been able to develop their projects with lower investment costs, remaining profitable.

Spatial aggregation: The simulation of hourly profiles over a year for all projects and the aggregation of the production profiles into the main transmission buses of the national electrical system produces aggregated wind production profiles. These profiles are a very valuable input to transmission planners and system operators, as they incorporate the benefits of spatial and temporal aggregation (including production correlation). The national aggregated production from all wind farms tend to a normal distribution while capacity is increased.

A large part of wind potential described here could only be unlocked by developing more transmission. This is why the development of transmission for renewable energy zones is fundamental. Otherwise, projects compete for the available transmission capacity and once one project has been developed the neighboring projects are blocked or limited to the limited remaining transmission capacity.

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