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How does El Niño Southern Oscillation impact the wind resource in Chile? A techno-economical assessment of the influence of El Niño and La Niña on the wind power

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ABSTRACT

This paper assesses the impact of the El Niño Southern Oscillation (ENSO) on the wind speed, energy production, as well as its impact on the value of potential wind projects at different sites across Chile. The study applies cyclostationary empirical orthogonal function (CSEOF) analysis to isolate the ENSO influence on the wind speed, and therefore on the energy output of nearly all current and potential wind farms in Chile. Finally, a review of techno-economical parameters is made to assess the economic impact of an ENSO event occurring at different years in the lifetime of a wind energy project. The main contribution of this work is to establish the locations in Chile where this climatic oscillation is important for the system planning, the energy forecasting and the risk assessment.

1. Introduction

The share of wind projects in the Chilean electrical system has increased from 0.18% (20 MW) of the total installed capacity in 2007 to 4.36% (906 MW) in September of 2015 [1], thereby supplying 3.33% (1.465 Terawatt hour) of the national energy production [2,3]. The estimation of the potential of the wind resource is fundamental for the development of new wind projects. However, understanding the temporal variability can be just as, or more important, especially when addressing topics related to prediction of the resource, operation of the projects, contract coverage and spot price exposure, financing and insurance, among others.

Most of the understanding regarding inter-annual wind resource variability is based either on relatively short measurements of the wind speed on existing or prospective sites, or on data from numerical predictions (Numerical Weather Prediction or NWP) or regional climate models [4]. The measure-correlate-predict (MCP) methods permit a characterization of the resource using only short measurement records, which is why they are the most commonly used methods in the industry. A major assumption in the MCP methods is that the wind is statistically stationary, which means that the historical wind speed distribution is invariantly propagated into the future [5]. This assumption is highly questionable when considering that most of the data records are relatively short with respect to the period of climatic oscillations such as El Niño Southern Oscillation (ENSO). ENSO consists of a warm phase called El Niño and a cold phase called La Niña. Each phase has a tremendous impact on the climate in Latin America and the Caribbean (Fig. 1), India, Oceania, the United States and Africa.

In Latin America, where hydroelectricity represents close to 50% of the total electricity generation [7], the effects of El Niño are essential to estimate precipitation and water availability [8,9]. Various studies regarding the effect of ENSO on the hydrology in Latin America have been developed [10–14]. However, the study of the ENSO impact on the wind regimes is still a pending challenge.

ENSO, as a climatic oscillation, can cause considerable changes to the statistical characteristics of the wind resource during the

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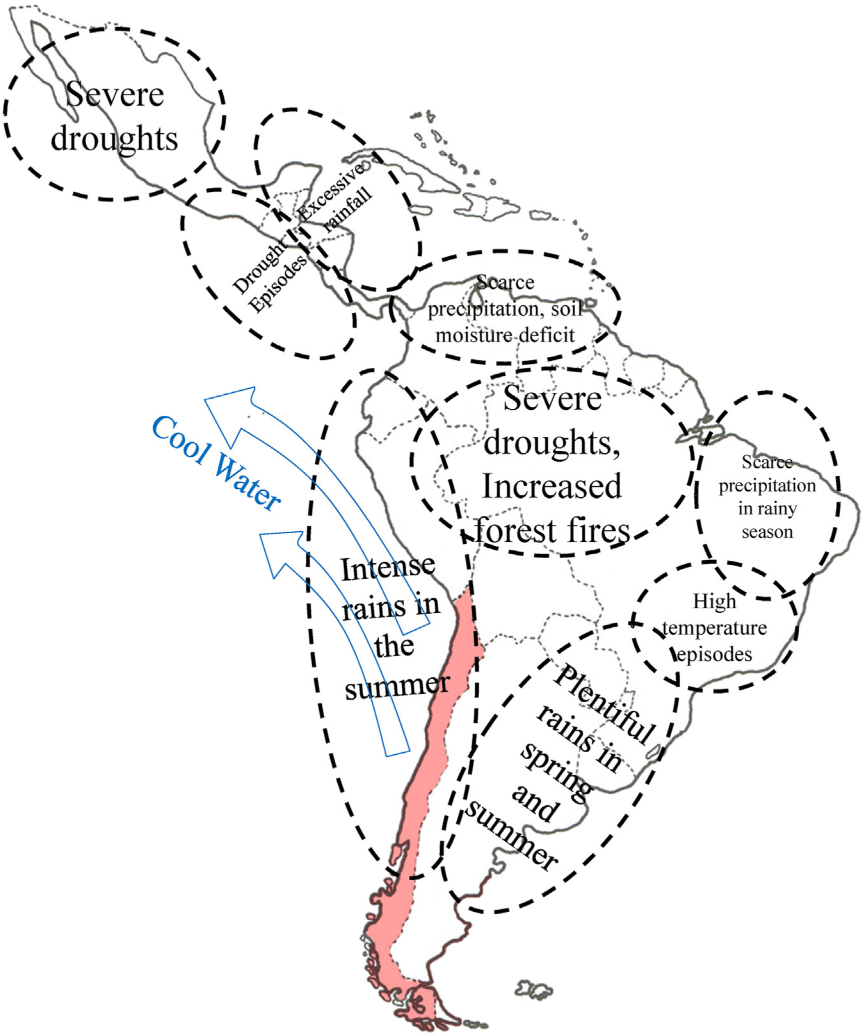


Fig. 1. Climate impacts of El Niño in Latin-America. Chile is highlighted. Based on [6].

lifetime of a project [4]. Therefore, determining the impact of these oscillations is of great importance, especially in Chile. This is due to the fact that the mean wind speed on most of the sites is relatively low, close to the limit for economic feasibility. On these sites the wind turbine generators (WTG) are frequently operated close to the cut-in speed and below the rated power. Therefore, a drop in wind speed will cause a reduction in production which is proportionally larger compared to sites with high wind speeds. On high speed sites, the WTG operate close to or above the rated speed and therefore the production is more stable (Fig. 2).

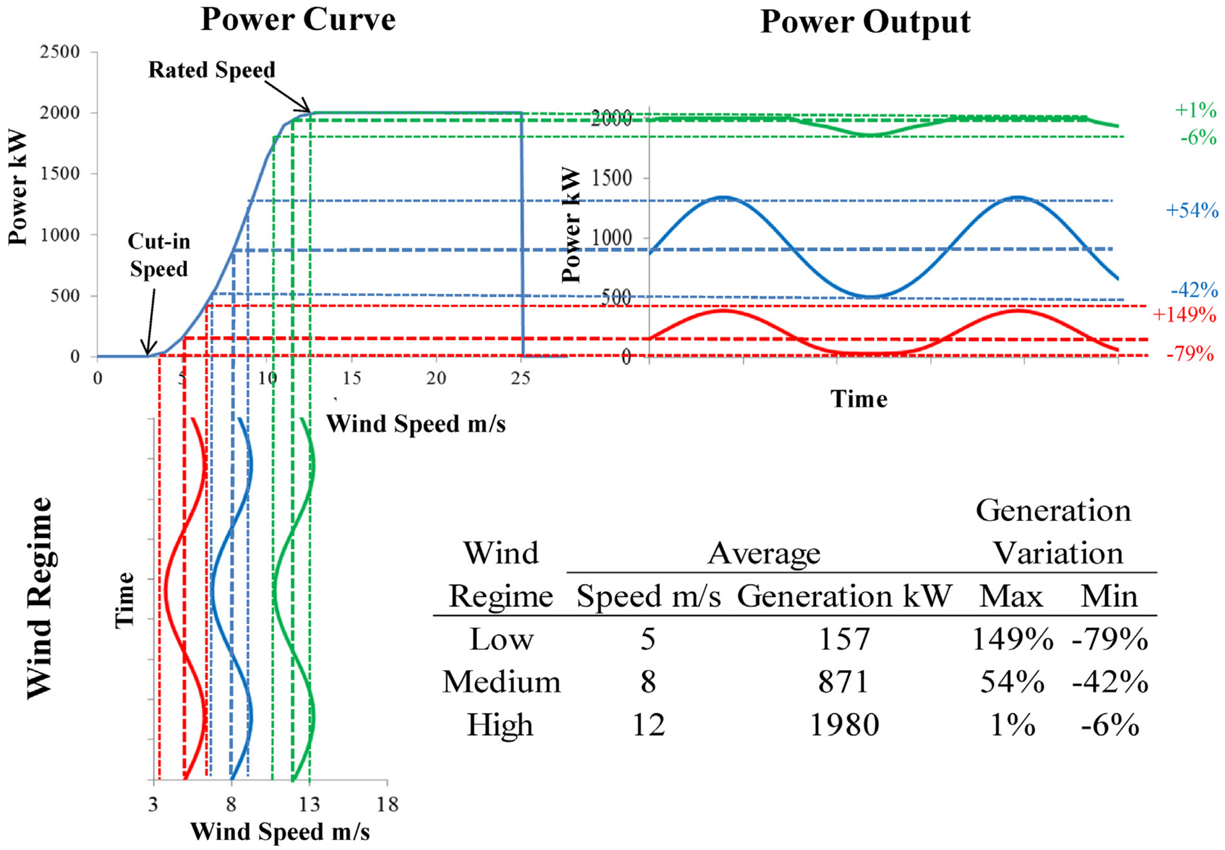
The objective of this study is to evaluate the effect of ENSO on wind projects across Chile, establishing its importance in the development of projects and in the prediction of the wind resource. To achieve this, the wind speed time series are decomposed to identify an ENSO-related climatic signal, for 22 sites representative of the wind potential in Chile. Based on this result, the impact on the wind power generation on these sites is calculated, to finally determine how this variation affects the value of a project on the different sites. The effect of ENSO is classified by events that occur during the cold phase (La Niña) and during the warm phase (El Niño), since the purpose is to determine in which zones the events of La Niña and El Niño are beneficial or harmful to the wind power production and the future industry development.

2. Data and methods

In order to identify the ENSO-related variability on a wind speed time series, it is necessary to use a decomposition which can isolate a specific climatic signal. In this work, the climatic signal is isolated by using cyclostationary empirical orthogonal functions (CSEOFs) [15,16]. The result of the methodology is a time series which represents the variation in the wind resource caused by ENSO. Another methodological alternative which is frequently used in climatic studies, are empirical orthogonal functions (EOFs). The EOFs are used for the study of patterns in the climatic variables, and assume that the temporal variability of the analyzed variable is stationary. However, it is observed that many geophysical variables typically show a cyclostationary behavior [17]. This means that their statistical properties vary cyclically with time [18]. Even though the EOFs can represent the cyclostationary signals through a superposition of multiple patterns, the CSEOFs allow for the explanation of these signals from one single pattern [17]. This increases their interpretability, and they have therefore been chosen for this study.

2.1. Analyzed sites and wind resource data

With the objective of identifying the influence of ENSO on the Chilean wind resource, 22 sites are chosen, belonging to the two



Wind	Average		Generation Variation	
Regime	Speed m/s	Generation kW	Max	Min
Low	5	157	149%	-79%
Medium	8	871	54%	-42%
High	12	1980	1%	-6%

Fig. 2. The effect of different wind regimes on the wind power output.

major electrical systems in Chile: Sistema Interconectado Central (SIC) and Sistema Interconectado del Norte Grande (SING). These systems supply 99.8% of the total energy consumption [19]. The sites were selected based on their proximity to operating wind farms, wind projects at different stages of development, and areas with wind potential without current project developments [20]. The selected sites provide a representation of existing and future wind projects in Chile. The coordinates of each analyzed site are shown in Table 1. Additionally, the topography of each site is presented, which is classified either as coast, valley or highland. This is to identify any possible relation between the ENSO effect on the wind resource and proximity to the ocean, altitude or other geographical variables.

For each site, the wind speed time series are obtained from a reconstruction made by the Weather Research Forecasting (WRF) model of the Explorador Eólico Nacional de Chile [21]. WRF is a non-hydrostatic model which solves the fundamental equations that control the atmospheric circulation in a three-dimensional grid. The model has been widely used in the study of wind energy, both for resource characterization and prediction of power production.

The retrieved data present the mean wind speed for each hour between January 1981 and December 2013. From this data the monthly average for each month is calculated, generating a time series of monthly frequency to which the CSEOF decomposition is applied. Public data on real wind speed measurements in Chile also exists [22]. However, this database does not cover records longer than 5 years, which is not enough to identify the impact of ENSO by a single mode, given that a record of at least 35 years is needed [23]. Therefore, the series obtained from the Explorador Eolico are used, even though this data record of 33 years is also shorter than required. To resolve this, a complementary methodology is applied, which is described in Section 2.3 regarding the regression of an ENSO index over one of its components.

2.2. Cyclostationary empirical orthogonal function decomposition of the wind speed

To identify the physical processes that explain the variability in the wind resource associated with ENSO, a CSEOF analysis is applied to the monthly anomaly of the wind speed for each site [17]. This provides *patterns* or *modes*, where each mode corresponds to Loading Vectors (LVs) and its respective Principal Component Time Series (PCTS). The anomaly of the wind is obtained by extracting the long-term average and the long-term trend from the monthly time series. The LVs are cyclical and show the physical evolution of the studied variable, which is repeated for each period. This period is called *nested period* and is selected a priori. The choice of the nested period is based on the understanding of the physical phenomena that is being studied. A nested period of one year has been shown to be effective to extract the variability associated with ENSO [24–28].

Using one year as a nested period, the decomposition generates 12 LVs (when using monthly data) where each one corresponds to the physical evolution of the studied process from month to month. The PCTS correspond to a stochastic modulation which represents the amplitude of the process at a given moment. For instance, the first CSEOF corresponds to an annual profile that is modulated over time (Fig. 3). This annual cycle is called Modulated Annual Cycle or MAC [29].

Table 1
Coordinates and features of analyzed sites: Operating wind farms and potential projects.

Zone	Coordinates		Region	Potential Zone[a]	Operative Projects	Topography
	Latitude	Longitude				
Loa	−21,64	−69,54	II	No	0	Valley
Calama	−22,49	−68,83	II	Yes	1	Highland
Taltal	−25,07	−69,59	II	Yes	1	Highland
Chañaral	−28,92	−71,47	III	Yes	0	Coast
Talinay	−30,84	−71,65	IV	Yes	2	Coast
Canela	−31,09	−71,62	IV	Yes	2	Coast
Totoral	−31,29	−71,62	IV	No	3	Coast
Llay-Llay	−32,83	−70,99	V	No	0	Valley
Valparaíso	−33,10	−71,64	V	No	0	Coast
Ucuquer	−34,04	−71,62	VI	No	1	Valley
Concepción	−36,79	−73,17	VIII	No	0	Coast
Arauco	−37,24	−73,58	VIII	Yes	0	Coast
Cuel	−37,39	−72,53	VIII	Yes	1	Valley
Curalinahue	−37,48	−73,46	VIII	Yes	0	Coast
Renaico	−37,69	−72,55	IX	Yes	0	Valley
Lebu	−37,71	−73,64	VIII	Yes	1	Coast
Temuco	−38,49	−73,25	IX	Yes	0	Valley
Valdivia	−39,92	−73,27	XIV	Yes	0	Coast
Purranque	−40,94	−73,75	X	Yes	0	Coast
Chiloé Norte	−41,90	−73,95	X	Yes	0	Coast
Chiloé Centro	−42,56	−73,92	X	Yes	1	Valley
Chiloé Sur	−43,12	−73,94	X	Yes	0	Valley

[a] Potential Zones defined by the Ministry of energy.

2.3. Regression analysis and identification of the El Niño Southern Oscillation

The second mode PCTS is highly correlated with the Multivariate ENSO Index (MEI) when the data record is sufficiently long (>35 years). The second CSEOF would then describe the effect of ENSO on the wind speed. However, since the data record is only 33 years a regression analysis is performed. All the PCTS, except for the first mode which is associated with the MAC, are linearly regressed onto the MEI in order to obtain a CSEOF associated with ENSO [17,24,26]. This regression yields an ENSO-related LV, that when multiplied by the MEI, gives the CSEOF of the ENSO's impact on the wind speed.

The resulting CSEOF describes the temporal and spatial variations of the wind speed caused by ENSO at the different sites across Chile. Nevertheless, the physical mechanisms that explain the relation between the ENSO fluctuations and the wind speed variations are not addressed in this study and further research on this topic is a pending challenge.

2.4. Wind energy estimation methodology

To calculate the impact of ENSO on the power generation, the monthly wind energy must be estimated from the monthly mean wind speed. This calculation is based on [30], where a cubic polynomial is fitted to the observed wind power and wind speed pairs, which are presented for the Canela site (Fig. 4). The fitting is based on least squares criteria with the following constraints:

1 Zero generation for zero monthly wind speed
2. Monthly capacity factor lower than or equal to 1
3. Monthly capacity factor greater than or equal to 0

The monthly wind energy is calculated by adding up the hourly generation for each month. The hourly generation is obtained by using the power curve of the WTG, $P(v)$, where v is the hourly wind speed. $P(v)$ is defined as a piecewise function, where the speeds between the cut-in speed and the rated speed are approximated to a fitted eleventh order polynomial, with a lower limit in zero and an upper limit in the rated power.

$$P(v)=\begin{cases}0, & \text{if } \; v<v_{cut-in}\, or\, v>v_{cut-off}\\ \min\left(\max\left(\sum_{i=0}^{11}a_i v^i,0\right),P_{rated}\right), & \text{if } \; v_{cut-in}<v<v_{rated}\\ P_{rated}, & \text{if } \qquad ;\end{cases} \tag{1}$$

The Vestas-V90 with a rated power (P_{rated}) of 2000 kW was chosen, since it is one of the WTG models most commonly installed in Chile [20]. It is used for instance in the Monte Redondo, Totoral, Talinay and Lebu wind farms. For this WTG, the cut-in speed ($v_{cut\text{-}in}$), the rated speed (v_{rated}) and the cut-off speed ($v_{cut\text{-}off}$), are 3 m/s, 12 m/s and 25 m/s respectively. The energy variations caused by ENSO are calculated using the monthly power curve. The variations are obtained by comparing the generation from the monthly wind speeds with and without the changes caused by ENSO.

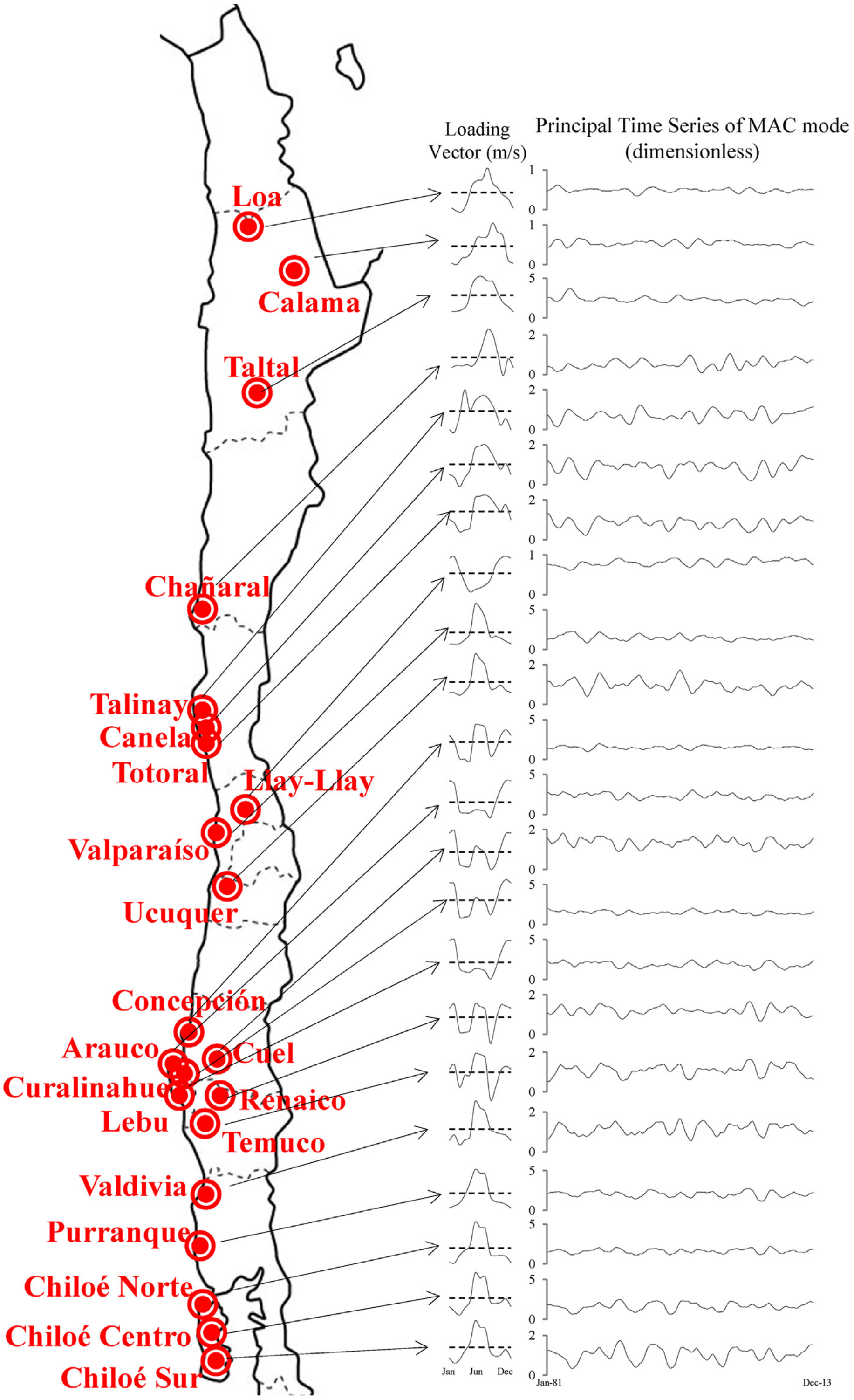


Fig. 3. Loading Vector and Principal Component Time Series of MAC mode (1st mode) at each site.

2.5. *Review of technical and economic parameters for wind projects*

The profitability of a wind farm depends as much on the technical factors, such as their installed capacity and produced energy, as on economic factors, like the investment cost, capital structure, interest rate, taxes, etc.

2.5.1. *Review of technical parameters for wind projects*

The power generation of a wind farm depends directly on the wind speed at the site where the project is located. The different wind classes are defined according to the average speed, turbulence and extreme gusts, which determines the turbine class to use according to international standard IEC61400-1. The production of the wind farm also experiences performance degradation over

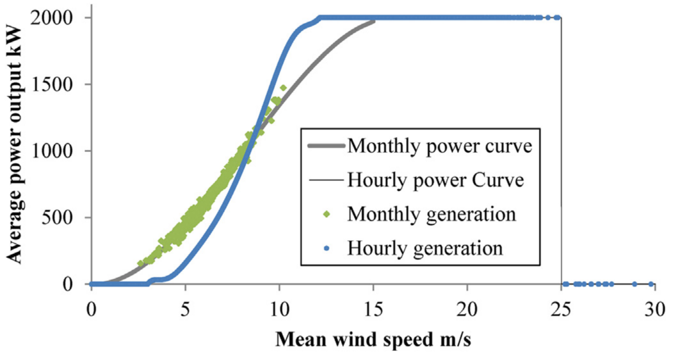


Fig. 4. Estimated monthly and hourly power curve for a Vestas V90 at the Canela site.

time. A detailed study of the wind farm degradation is developed in Ref. [31]. This work concludes that the annual degradation is −1.6% ± 0.2%. Nevertheless, the authors state that it is not possible to determine if it has any functional form due to the lack of data.

In order to calculate the total generation of a project it is necessary to consider the losses of the generation system, transformation and internal distribution of the wind farm. The different sources of losses are listed as follows: 8% from availability, 2.3% from electrical, 1.4% from WTG, 4% from the effect of the environment and 2.1% from wake effect. These add up a total loss of 16.7% [32,33].

2.5.2. Review of economic parameters for wind projects

The main economic parameter of a project is the sale price of the energy, which is assumed to be 85 USD/MWh. This is according to the “knot price”, which corresponds to the present value of the market clearing prices in a horizon of 4 years. This was calculated by the Comisión Nacional de Energía in October of 2014 for SIC (CNE 2014).

In order to calculate the economic value of a project, the net present value (NPV) method is used, which requires a discount rate. The main methodology used for the rate calculation is the WACC (Weighted Average Cost of Capital) (2) which weighs the cost of capital from diverse sources of funding.

$$WACC = \frac{E}{Inv} r_e + \frac{D}{Inv} r_d (1 - \tau) \qquad (2)$$

Here E is the equity of the project, D is the debt, Inv is the total investment considering debt and equity ($Inv = E + D$), τ is the tax rate and r_e and r_d is the equity rate and the debt rate, respectively. The equity rate is calculated from Equation (3), derived from the Capital Asset Pricing Model (CAPM).

$$r_e = r_f + \beta r_M + r_c \qquad (3)$$

Here r_f is the risk-free rate, r_c is the country risk, r_M is the market risk premium and β is a measure of comparative risk between renewable energy projects and the rest of the market during a period of time. For the economic evaluation a 40% equity and 60% debt is considered, using a debt rate of 7% [34–38]. A tax rate of 25% is used (according to the Chilean law by the beginning of 2017 [39]). Levered β is 1.6 (unlevered β for a renewable energy project is 0.74) [40], risk-free rate is 1.9%, market risk premium is 4.4% and country risk is 0.5% (valid for Chile) [41]. These values give an equity rate of 9.44% and a WACC of 7.03% according to Equations (3) and (2), respectively.

The rest of the economic parameters are the investment cost, operational and maintenance cost (O&M), life-time of the project and salvage value. The values of these parameters were obtained through a review of the literature related to wind projects evaluation. In Table 2 the result of the review is summarized, showing the respective sources and the used value. The investment and O&M costs were modelled depending on the WTG capacity, in order to reflect economies of scale.

2.5.3. Method to assess value variations of wind projects

In order to assess the economic impact of ENSO on the wind energy industry in Chile, the Net Present Value (NPV) is calculated [42]. This method is widely used for economic evaluation of any type of projects, and it is one of the most commonly used methods to evaluate wind projects [34,36,43–52]. NPV (4) discounts the future cash flows of the project, according to the discount rate of each period. The discount rate is commonly assumed to be constant.

Table 2
Economical parameters and references.

Parameters	Selected value	Conclusions from literature review	References
Operational and Maintenance Costs	2.1% of total investment	A model was fitted for O&M versus WTG rated power Model*: $K_1 + A_1 \exp(-Ps_1)$ $K_1 = 1.5\%$, $A_1 = 3.5\%$, $s_1 = 0.085\%$	(Fazelpour et al. [57]; Colmenar-Santos et al. [34]; Schallenberg-Rodríguez & Notario-del Pino [58]; Nedaei et al. [46]; Caralis et al. [35]; Schallenberg-Rodriguez [59]; Diaf & Notton [60]; Mohammadi & Mostafaeipour [50]; Ohunakin & Akinnawonu [49]; Adaramola et al. [63]; Rehman et al. [61]; Friedman [38]; Gökçek & Genç [64]; Hoogwijk et al. [66]; Rehman et al. [62])
Investment Cost	1500 USD/kW	A model was fitted for investment versus WTG rated power Model[a]: $(K_1 + A_1 \exp(-Ps_1))(K_2 + A_2 \exp(-Ps_2))$ $K_1 = 1100$, $A_1 = 1400$, $s_1 = 0.0055$, $K_2 = 0.39$, $A_2 = 0.31$ $s_2 = 0.002$	(Kaldellis & Gavras [52]; Fazelpour et al. [57]; Mohammadi & Mostafaeipour [50]; Rehman et al. [61]; Rehman et al. [62]; Gökçek & Genç [64]; Diaf & Notton [60]; Ohunakin & Akinnawonu [49]; Hoogwijk et al. [66]; Schallenberg-Rodríguez & Notario-del Pino [58]; Schallenberg-Rodriguez [59]; Nedaei et al. [46]; Colmenar-Santos et al. [34]; Friedman [38]; Adaramola et al. [63]; Xydis [36]; Caralis et al. [35])
Lifetime of the project	20 years	Most references use 20 years A couple of references uses 25 or 30 years	(Caralis et al. [35]; Friedman [38]; Schallenberg-Rodríguez & Notario-del Pino [58]; Schallenberg-Rodriguez [59]; Xydis [36]; Diaf & Notton [60]; Marafia & Ashour [65]; Rehman et al. [62]; Rehman et al. [61]; Nedaei et al. [46]; Harijan et al. [48]; Hoogwijk et al. [66]; Gökçek & Genç [64]; Ohunakin & Akinnawonu [49]; Adaramola et al. [63]; Mohammadi & Mostafaeipour [50]; Fazelpour et al. [57]; Colmenar-Santos et al. [34]; Grassi et al. [37])
Salvage value	5% of total investment	Most references neglect this item. Few references use 5% and 10%	(Diaf & Notton [60]; Rehman et al. [61]; Rehman et al. [62]; Nedaei et al. [46]; Harijan et al. [48]; Ohunakin & Akinnawonu [49])

[a] P: rated power, s_i: rate change; K_i, A_i are constants.

Table 3
Monthly wind speed averages considering only months without ENSO events at each site.

Site	Monthly wind speed average m/s												Mean m/s
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Loa	4,7	4,6	4,6	4,9	5,6	5,8	5,9	6,4	5,7	5,5	5,2	5,1	5,3
Calama	7,0	6,9	7,2	7,3	7,6	8,1	8,1	8,2	8,8	8,3	8,2	7,2	7,7
Taltal	5,3	5,6	5,9	6,8	10,7	11,8	12,0	11,4	11,4	9,2	7,3	6,2	8,6
Chañaral	6,6	6,7	6,5	6,7	6,6	7,0	7,4	8,2	8,0	7,1	5,9	6,8	6,9
Talinay	4,6	4,7	5,5	7,1	5,7	6,4	6,5	6,8	6,3	5,8	4,7	5,3	5,8
Canela	5,6	5,6	4,5	5,4	5,9	7,4	7,4	7,8	7,2	6,7	5,6	6,2	6,3
Totoral	5,5	5,4	4,5	4,6	4,9	6,7	6,8	7,1	6,8	6,4	5,7	6,3	5,9
Llay-Llay	5,3	5,4	4,6	3,8	3,2	3,3	3,4	3,6	4,0	5,0	5,4	5,6	4,4
Valparaíso	2,5	2,6	2,6	3,0	3,8	6,9	6,9	5,6	3,4	3,5	3,2	2,8	3,9
Ucuquer	5,1	5,2	5,0	5,3	5,8	8,1	7,8	7,3	5,5	5,5	5,8	5,3	6,0
Concepción	7,1	6,4	4,4	4,3	4,0	8,2	8,4	8,0	4,7	5,4	7,1	8,0	6,3
Arauco	12,7	12,1	7,0	6,4	6,6	7,0	7,1	6,6	5,6	8,6	10,8	12,3	8,6
Cuel	8,7	9,2	5,6	5,0	5,3	7,1	7,1	6,5	4,9	5,5	7,2	8,5	6,7
Curalinahue	9,1	9,1	5,1	4,8	5,2	7,1	7,2	6,6	5,2	6,8	8,6	9,4	7,0
Renaico	11,2	11,4	7,1	6,3	6,4	6,8	6,9	6,3	5,3	7,0	9,2	10,6	7,9
Lebu	8,2	8,7	6,1	5,8	6,2	8,5	8,4	7,8	4,8	7,0	8,5	8,4	7,4
Temuco	7,6	8,4	6,2	7,1	7,5	8,9	9,1	8,5	4,9	6,1	7,7	8,2	7,5
Valdivia	3,4	4,1	3,1	3,7	4,1	7,2	6,7	6,2	4,7	4,2	4,1	4,3	4,6
Purranque	6,2	7,0	7,3	9,0	10,9	13,2	12,6	12,2	8,5	7,3	7,5	7,6	9,1
Chiloé Norte	4,6	4,9	5,7	6,5	7,2	10,3	9,6	9,3	6,0	5,5	5,9	6,0	6,8
Chiloé Centro	6,7	6,6	5,8	6,9	8,1	11,7	11,0	11,3	7,8	7,1	7,7	8,4	8,3
Chiloé Sur	5,7	5,7	5,7	6,7	7,6	9,4	8,7	8,7	6,6	5,9	6,3	7,0	7,0
Mean m/s	6,5	6,6	5,5	5,8	6,3	8,0	8,0	7,7	6,2	6,3	6,7	7,1	6,7

Table 4
Monthly capacity factor corresponding to monthly wind speeds averages of Table 3.

Site	Monthly capacity factor % (Without losses)												Mean %
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Loa	17,7	17,2	17,0	19,6	25,3	27,0	27,8	31,5	26,1	24,4	22,1	20,8	23,0
Calama	40,1	39,5	42,4	43,0	45,9	51,3	51,8	52,6	58,6	53,8	52,4	42,0	47,8
Taltal	22,2	24,3	26,8	35,1	71,0	79,8	81,2	76,9	77,3	57,7	39,6	29,7	51,8
Chañaral	34,8	35,3	34,1	35,5	34,9	38,8	41,9	49,7	47,8	39,2	27,8	36,7	38,0
Talinay	16,2	17,1	23,1	37,2	25,1	30,6	31,9	34,2	29,9	26,1	16,7	21,7	25,8
Canela	26,6	27,1	18,3	24,8	29,5	42,7	42,7	46,9	41,6	36,8	27,2	32,5	33,1
Totoral	23,3	23,0	16,1	16,9	18,7	34,2	35,2	37,9	34,9	31,7	25,4	30,3	27,3
Llay-Llay	26,4	27,1	20,2	13,6	8,9	9,6	10,6	11,9	14,7	23,2	27,6	29,3	18,6
Valparaíso	4	4,3	4,1	6,1	10,2	33,9	33,2	22,7	7,9	8,4	6,7	5,0	12,2
Ucuquer	20,6	21,4	20,0	22,1	26,4	45,7	43,8	39,4	23,7	23,9	25,9	22,2	27,9
Concepción	37,4	30,7	14,9	14,0	12,4	47,1	49,6	45,7	16,7	22,6	37,3	45,1	31,1
Arauco	85,4	81,9	39,1	33,3	35,1	38,5	39,4	35,5	25,9	53,6	72,8	83,1	52,0
Cuel	56,1	60,1	26,1	21,5	23,7	40,7	40,1	34,8	20,7	25,4	41,6	54,1	37,1
Curalinahue	59,8	59,6	21,5	19,4	22,9	40,0	40,4	35,0	22,5	36,9	55,0	62,1	39,6
Renaico	78,0	79,5	41,3	33,1	34,3	38,0	39,3	33,7	24,3	39,9	61,7	73,8	48,1
Lebu	49,9	54,7	29,6	27,5	31,0	52,8	52,2	45,8	18,8	38,4	53,2	51,9	42,1
Temuco	41,9	48,8	29,2	37,6	41,3	53,4	55,3	49,9	18,9	28,8	42,4	47,2	41,2
Valdivia	9,1	13,8	7,3	10,8	13,7	40,5	35,9	30,8	18,6	14,5	14,1	14,9	18,7
Purranque	30,1	36,3	39,1	53,2	68,4	80,5	78,1	75,9	49,7	39,3	41,3	42,1	52,8
Chiloé Norte	16,8	18,4	25,1	32,5	39,0	67,8	61,2	58,9	27,4	23,9	26,9	27,7	35,5
Chiloé Centro	33,2	32,9	26,3	35,4	44,7	69,6	65,4	67,2	41,9	36,5	41,7	46,7	45,1
Chiloé Sur	24,5	24,4	24,8	33,0	41,1	57,9	52,1	52,1	32,2	26,2	30,0	35,5	36,2
Mean %	34,3	35,3	24,8	27,5	32,0	46,4	45,9	44,0	30,9	32,3	35,9	38,8	35,7

Table 5
Frequency of ENSO events for each month during the recorded period. Values in percentage. Months without ENSO events are presented in bold.

Event	Frequency of the ENSO event between Jan-1981 and Dec-2013%											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Ago	Sep	Oct	Nov	Dec
Very Strong Niño	20	**0**	**0**	**0**	**0**	**0**	**0**	**0**	11	10	20	20
Strong Niño	10	33	13	**0**	**0**	**0**	**0**	29	22	10	**0**	**0**
Moderate Niño	20	22	38	50	29	25	25	14	11	30	50	70
Weak Niño	50	44	50	50	71	75	75	57	56	50	30	10
Weak Niña	62	58	56	100	100	60	60	50	50	50	45	54
Moderate Niña	23	42	44	**0**	**0**	40	40	50	50	50	45	31
Strong Niña	15	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	9	15

$$NPV = \sum_{t=1}^{n} \frac{F_t}{(1+WACC)^t} - I_0 \tag{4}$$

F_t and I_0 is the cash flow in year t and the initial investment of the project, respectively, while n is the investment horizon, which typically coincides with the life-time according to the literature (see the references in Table 2). The variations in NPV caused by ENSO are related to the variations in the energy production. These energy variations are calculated from the ENSO effect on the capacity factor corresponding to the monthly wind speed of Table 3 (Table 4).

3. Results

The CSEOF decomposition and PCTS regression result in an ENSO effect on the wind speed time series. From this series the average impact of the different intensities of ENSO is calculated for each month of the year. ENSO is classified according to the intensity of El Niño or La Niña as very strong, strong, moderate or weak. This classification is based on the Oceanic Niño Index (ONI) [53], where positive values indicate an El Niño event (warm phase) and negatives values a La Niña event (cold phase). ONI values over or below ±2 indicates a very strong event, between 2 and 1.5 strong events, between 1.5 and 1 moderate events and between 1 and 0.5 weak events. Months with an index between ±0.5 are considered to be ENSO-neutral. During the 33 years recorded there are no very strong La Niña events, leaving only 7 possible classifications. Table 5 presents the frequency of the events in relation to the total events of El Niño or La Niña in a respective month, for the whole data record.

When knowing the ENSO impact on the wind resource of a site, it is possible to determine the economic influence that it would have on a wind farm located nearby. In order to calculate this impact, the production of a wind farm is estimated by considering the presence of an ENSO event during one year of the total life-time. The impacted year is varied to demonstrate how the effect is mitigated when the ENSO event occurs further into the future.

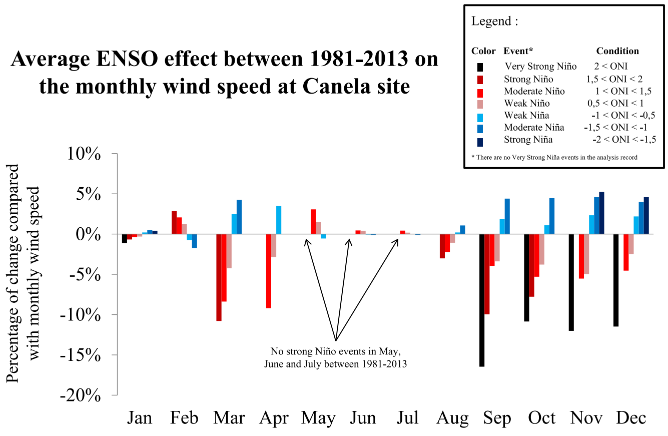


Fig. 5. A detailed example of ENSO impact on the wind speed at the Canela site.

3.1. Impact of ENSO on the wind speed in Chile

In the central-north coast of Chile, in the surroundings of the Canela commune, there is an important wind development pole that presents 9 operative wind farms that already add up to around 590 MW [19]. Additionally, there are other wind projects at different stages of development. This wind pole is represented in this work by the Totoral and Canela sites. Fig. 5 presents the impact of ENSO events classified by intensity (marked with different colors) for every month of the year. The impact in percentage expresses the average change in relation to the monthly wind speed. Thereby it is possible to identify the effect of ENSO on the monthly wind speed throughout the year, for different intensities of El Niño and La Niña. It can be concluded, for instance, that at the Canela zone El Niño significantly decreases the wind speed and power generation from September to December, while La Niña increases it with a lower intensity during the same months.

As mentioned earlier, for some months between January 1981 and December 2013 there are no historical records of strong or very strong El Niño events, or moderate or strong La Niña events. For instance, in Fig. 5 for the month of April, there are only records of weak and moderate events of El Niño, and weak events of La Niña.

La Niña is the cold phase of ENSO, and its effect is the opposite of El Niño for a given month. La Niña affects the wind speed with more than 2% for 28% of the months, while for 98% of the sites the variation does not exceed 6%. On the sites where a wind farm is present, La Niña tends to increase the available resource. However, the effect tends to be lower compared to the impact of El Niño.

3.2. Impact of ENSO on the wind power in Chile

The impact of ENSO in the energy production of a wind farm is not necessarily proportional to the variation of the wind. This difference depends not only on the mean wind speed at the site, but also on the wind speed distribution over time. In Fig. 6 the average energy variations are shown for every month of the year at the analyzed sites. Similar to what was done with the wind speed, the impact on wind power is classified according to the El Niño and La Niña intensities. Fig. 6 shows the same type of figure as used for Canela, for every analyzed site in Chile, for both the effect on wind speed and wind power. The same scale is used in order to be able to compare the sites and orders of magnitude of variations in speed and energy.

The sites of the *VIII region*, corresponding to Arauco, Cuel, Curalinahue and Renaico, are located in an area with the highest

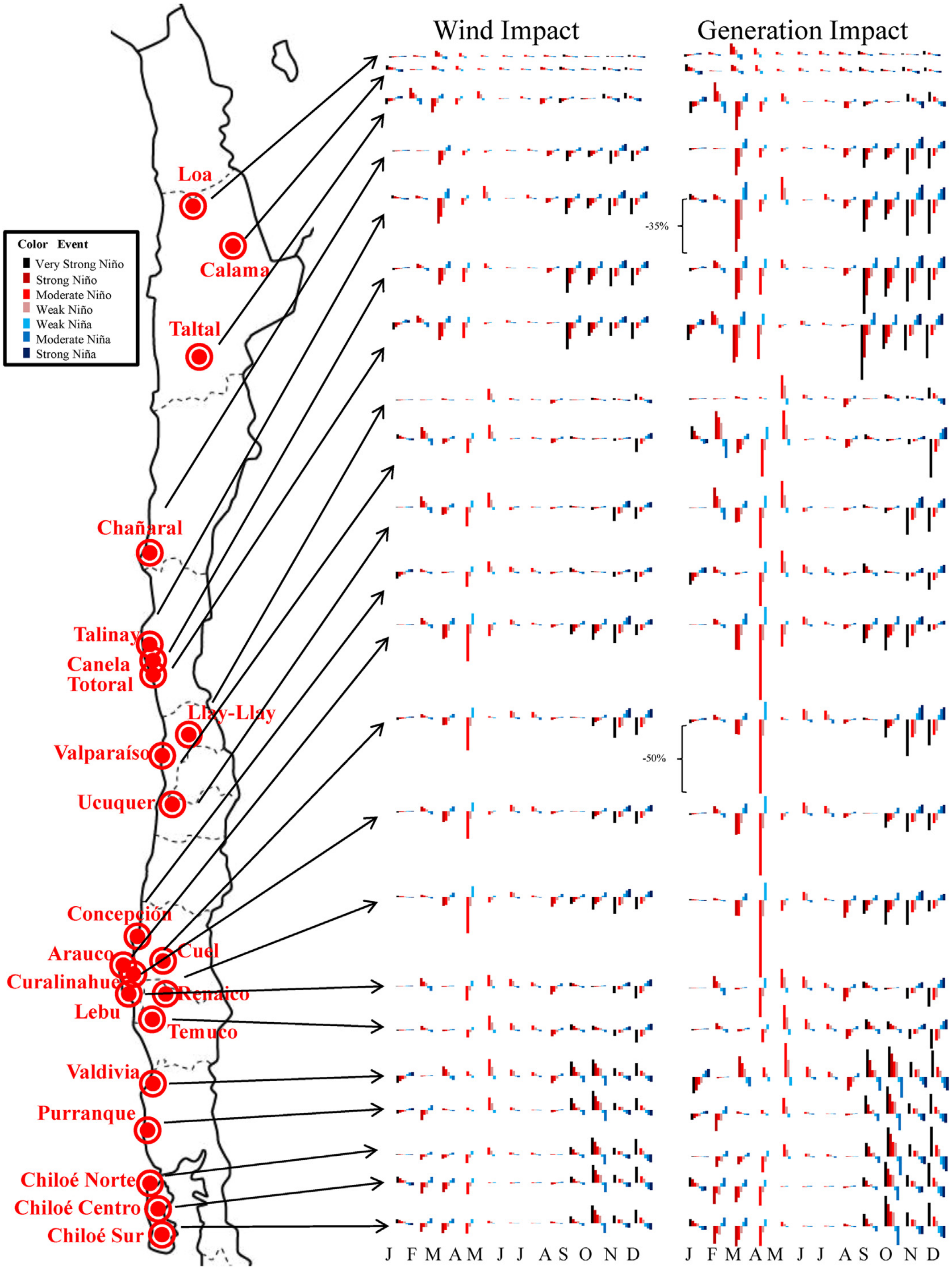


Fig. 6. ENSO effect on the Chilean wind resource. Impact on the wind speed (left) and on the energy production (right).

impact of ENSO. When there is no ENSO, the mean wind speed in April is between 4.8 m/s and 6.4 m/s (Table 3). Because of these low wind speeds, the average wind speed decrease of about 20% caused by a moderate El Niño event decreases the production with between 40% and 50%.

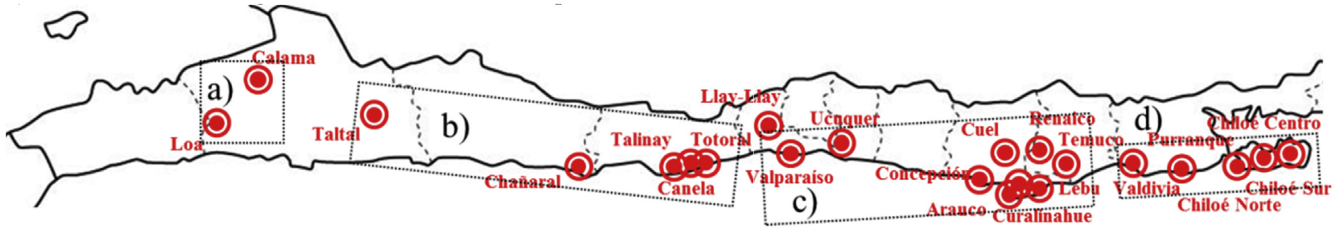
In the south of Chile, from the *regions VIII* to *IX*, the wind farms Cuel and Lebu are installed, and here there also exists a great wind energy potential in the coastal areas and the nearby valleys. In this extensive area, El Niño and La Niña do not have a significant impact most of the year, and strong events barely affect the production with about 12%. However, a strong decrease in the production is caused by El Niño in April, reaching about 42% in average for a moderate event. The effect of a very strong event is unknown, given that there are no records of these events in April for the analyzed period, but the impact is expected to be larger.

3.2.1. Spatial analysis of the influence of ENSO on the wind power in Chile

The sites are grouped by the similarities of the profile of the ENSO impact on the resource (Table 6). It makes sense to group

Table 6
Classified zones according to the ENSO impact profiles.

Zone		Sites
a) North	Loa – Calama	Loa, Calama
b) North-central	Taltal - IV region	Taltal, Chañaral, Talinay, Canela y Totoral
c) South central	V-VIII region	Valparaíso, Ucuquer, Concepción, Arauco, Cuel, Curalinahue, Renaico, Lebu y Temuco
d) South	XVI-X region	Valdivia, Purranque, Chiloé



them from north to south, since there is a strong relation between latitude and the ENSO effect on the wind resource. Four zones with similar impact profiles are identified, where each site can be classified except for Llay-Llay. The first zone covers the north of the *II region* with Loa and Calama, the second covers from the south of the *II region* to the *IV region*, composed by all the sites between Taltal and Totoral, thereby comprising an extensive area. The third zone covers from Valparaíso to Temuco, between the *V* and the *IX region.* The last identified zone includes the southernmost regions of SIC, grouping the sites from Valdivia to Chiloé (*XVI* and *X region*).

In the northern zone of *Loa-Calama* the effect of El Niño is predominantly positive, but low during the year, with a slightly higher intensity during February and March. In the northern-central zone of *Taltal-IV region*, the sites present similar ENSO effect profiles during the whole year, where El Niño affects mainly negatively from February to December. The intensity of this decrease is higher in March and between September and December. While there does exist a great similarity between all the sites of this zone, there seems to be a transition in the profile from Taltal to Talinay, where the Chañaral site acts as an intermediate between the types of profiles on these sites.

The *IV region*, on the central-north coast of Chile, where the projects Canela, Punta Colorada, El Arrayan, Talinay, Los Cururos, Monte Redondo, Punta Palmera and Totoral are situated, both El Niño and La Niña have high intensities between September and December. During this season, El Niño decreases the power production with 11% in average, but can reach 17% for strong or very strong events. La Niña has the opposite effect, although with a lower intensity, increasing the wind energy production with 5% in average, reaching 8% for events with high intensity.

For the sites belonging to the central-southern zone of the *V-VIII region*, El Niño has a very strong and negative impact on the month of April. The opposite effect occurs in May in most sites. However, the intensity of the impact during this month varies a lot between the different sites. Another large and negative impact of El Niño on these sites occurs at the end of the year, between November and December. However, in this case the impact is not as strong as in April. For the rest of the months El Niño generally has a positive effect with low intensity, although this is not a general rule for all the sites.

The southern zone *XVI-X region* behaves similarly to the zone *V-VIII region* in April. However, ENSO has an opposite effect between September and December in this zone, where there is an important increase in the wind speed because of El Niño.

It is important to determine if the topography of the site is a relevant factor in relation with the ENSO effect. From the chosen sites there are two regions that allow comparing coast and valley, since they contain projects with both types of topography: the *V region* has Llay-Llay in the valley and Valparaíso on the coast, while the *VIII region* has Arauco and Lebu on the coast, and Renaico and Cuel in the valley. In these regions, the topographies (coast and valley) do not have a clear influence and the dominating factor seems to be the latitude (as discussed above) regardless of the topography. Even though ENSO has an opposite effect in some months, it is not possible to establish a general rule. The same conclusion is obtained when comparing highland and valley, with Calama and Loa. They have not only similar profile shapes, but also a similarity in the magnitude of the effects, again indicating that latitude is the prevalent factor.

Due to the significant amount of ENSO events during the lifetime of a wind farm, it is expected that ENSO affects the accuracy of the energy potential estimation of a wind power project. The sum of minor changes during a long period could generate a major deviation in the total production. In the next section, the effect of an ENSO event during a year will be analyzed from an economic perspective in order to assess this accumulated impact. It is important to state that the long term variability in South America is not only attributable to ENSO, since the Indian Ocean Dipole and the Antarctic Oscillation also could play an important role [54,55]. Nevertheless, this paper focused on ENSO because of its important role in natural resources in the last years [56].

3.3. Economic assessment of the impact of ENSO in the wind farm projects

With the parameters previously described in Section 2.5, the impact of an ENSO event in different years of the project is simulated and valorized. For instance: What would happen if El Niño occurs during the first year of operation of the project? What happens if La Niña occurs during the third year of operation of the project? To assess this, the NPV is calculated with Eq. (4) for each ENSO intensity occurring at different years of the life-time of the project.

In the months in which there are no registered ENSO events of high intensity, the effect is calculated using the ratio between strong and weak events in other months. For example, the month of February only has registers of moderate and weak ENSO events. To determine the impact of a hypothetical strong El Niño, the average ratio between the impact of a strong El Niño and a weak El Niño for January, September, October, November and December is calculated. Then, the effect of the hypothetical strong El Niño is equal to the effect of the weak El Niño adjusted by this ratio. This method is proposed to account for the impact of a hypothetical strong event, when there is a lack of recorded events in the data.

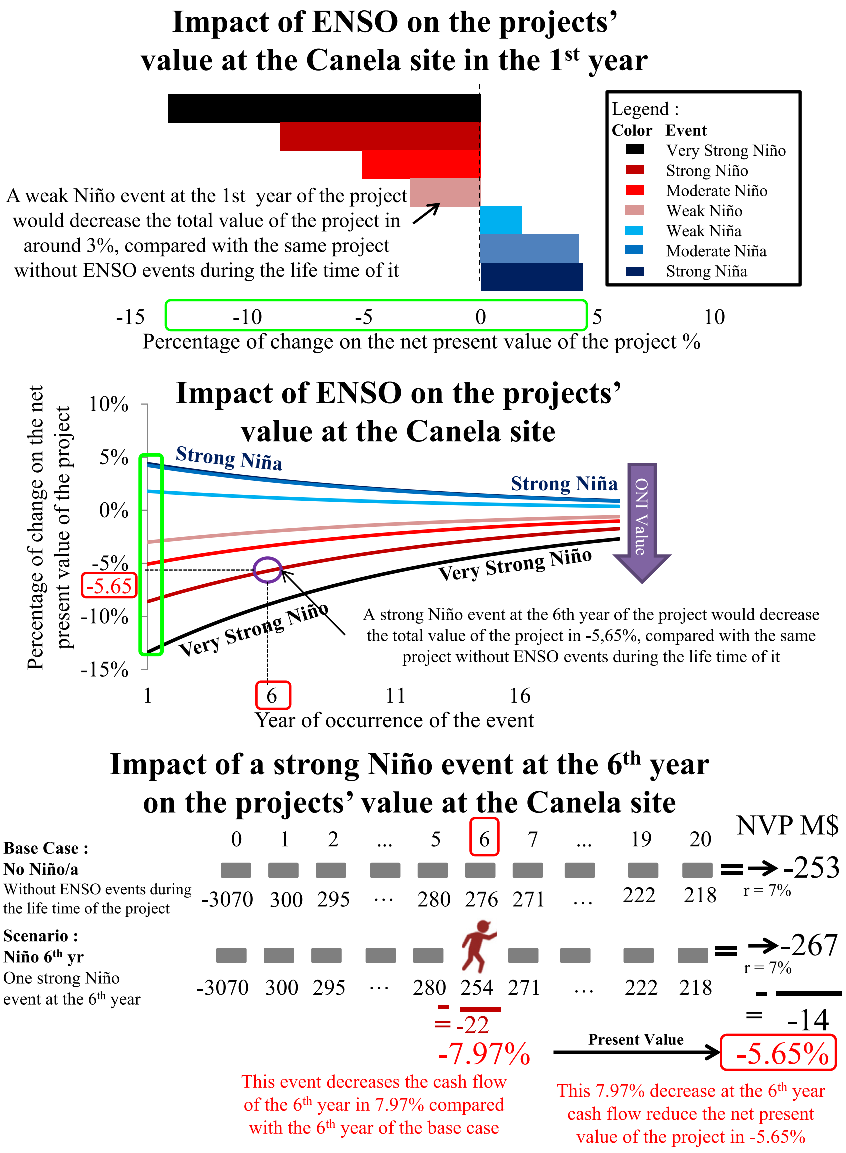


Fig. 7. A detailed example of the ENSO impact on the project value at the Loa site. Impact during the first year (top), impact during different years (center) and a detailed example of an impact during the 6th year (bottom).

In Fig. 7 the effect of the different intensities of ENSO on the NPV of a project at the Loa site is presented, with the events occurring at different years. The variations of NPV are in relation to the same project without any ENSO events during the life-time. The purpose is to visualize how the economic impact is reduced when the event occurs further into the future. Additionally, the impact of an event during the first year is detailed in order to compare the effect of the different intensities. The economic impact of ENSO at every site is shown in Fig. 8.

To properly interpret these results, it must be considered that a project can be hit about 3–4 times by any of the ENSO events. Nevertheless, over the last years, the frequency of El Niño has increased compared with La Niña. This is very important to consider in a project that is negatively affected by El Niño, making ENSO a factor that must be included in the development of projects in that area. The geographical classification previously made does not necessarily fit with the economic impact. This is due to the fact that the economic effects depend on the mean wind speed and the capacity factor at the site. A variation of 20% in the wind speed is not the same if the mean speed is 9 m/s compared to 5 m/s, especially when transformed into energy.

Cuel and Chiloé Norte are special sites since the impact of an El Niño event can change the value of the project about 30%. This is because the wind speed variations are almost duplicated in the generation. As previously mentioned, during the life-time several ENSO events can occur, which means that although the effect is great at these sites, the total impact of ENSO will depend on the combination of events and on the moment at which these occur.

At the Temuco site all the ENSO events have a positive impact on the value of the project. This does not mean that ENSO cannot decrease the wind speed during a specific month, but the total effect during a year is positive. This benefit of ENSO is low, reaching slightly less than 2% for a very strong El Niño, but no more than 0.3% for weak events. In this type of wind farms it would be possible to offer supply contracts with a special condition related to the presence of El Niño, knowing that this event will increase the production. It is important to emphasize that this special site has a

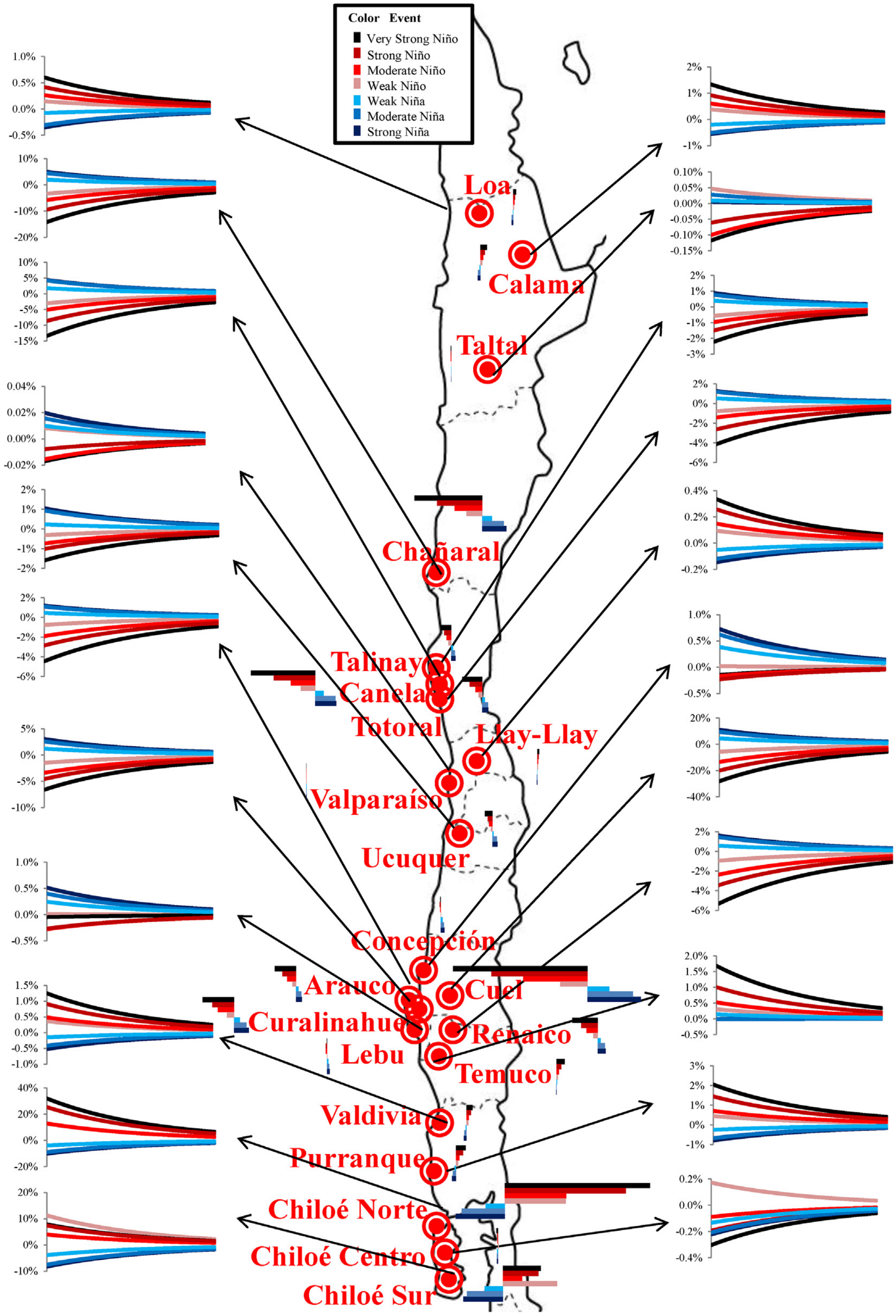


Fig. 8. Effect on the net present value of the project for ENSO events occurring during different years.

high potential, where the mean speed without ENSO events is 7.5 m/s.

On the sites of Loa, Taltal, Valparaiso, Llay-Llay, Lebu and Chiloé Centro the impact of ENSO is relatively low. This is especially the case for the Valparaiso site, where extreme events such as a very strong El Niño has less than a 0.02% impact on the value of the project, if it occurs during the first year. This makes the site practically immune to ENSO. An important characteristic of the Taltal, Lebu and Chiloé Centro sites is that they have high wind speeds (8.6 m/s, 7.4% and 8.3 m/s respectively), which makes them attractive sites given the considerable potential. Additionally, the low variability at these sites, at least with respect to the variability related to ENSO, means a lower risk.

In the selected sites belonging to the coast of the *IV region*, composed by Talinay, Totoral, Canela and Chañaral, there is a large negative impact of El Niño between September and December. This impact in annual terms is considerable, which could be observed from the El Niño impact in the value of a project, reaching about 14%. This would explain the performance is lower than expected [20], since the intensity of El Niño events have increased compared with La Niña over the last 100 years, possibly due to the global warming [23].

ENSO generally has a large effect on the value of the wind projects at the evaluated sites, and even weak and moderate events can modify the economy of a project. 34% of the weak events of ENSO can vary the valuing with more than 2% if they occur during the first year of operation of a wind project, while close to 14% of the weak events can vary the value with more than 6%. For 95% of the weak events of ENSO, the variation in the value of the project was less than 16%. For the moderate events of ENSO, 34% of the sites are affected with more than 2% in the value of the projects, and 14% of the sites experience a variation larger than 8%. The frequency of both the weak and the moderate events is not negligible, which means that the previous numbers prove the importance of explicitly including ENSO in the forecasting of the resource and in the economical evaluation.

4. Conclusions

The ocean-atmospheric oscillations such as El Niño and La Niña are responsible for significant changes in precipitation and in cloudiness in different areas of Latin America, as well as in Oceania, the United States and the south of Africa. This effect has important implications in the energy production of hydropower, wind and solar projects in various regions, but studies have mainly been focused on the effect on traditional hydropower plants. Unconventional energy sources, such as wind and sun, require more investigation in order to consider this effect in the calculation of the potential of the resource. This is the first work done on the modelling of the impact of ENSO on the power generation and valuing of wind projects, and only one publication was found that modelled the relation between ENSO and the wind, for North America and from a geophysical approach [4]. Hamlington's work has been a pioneer in the application of CSEOF decomposition to identify the ENSO effect on wind, and has served as a methodological base for the present article.

El Niño, the warm phase of ENSO, reduces the wind speed and the wind power production in most of the sites in the central-north of Chile where there are wind farms in operation, as well as in areas where the wind potential has not yet been exploited. However, the magnitude and sometimes the sign depend on the analyzed site and the month of which the phenomena occur. El Niño, when it occurs, affects the wind speed with more than 4% for 26% of the analyzed months, and affects less than 12% for 97% of the months. However, the effects can be much larger when observing some months and events in particular.

In Chile, the months that are shown to be most sensitive to ENSO are May and April. 50% of the May months where El Niño was present have variations in the production above 4%, and this threshold is overcome in 55% of the months of April where La Niña was present. On the other hand, August and June are the months in which ENSO has the lowest impact on the wind power. In the presence of El Niño in August, the energy varied less than 2% for 98% of the months, and for June, La Niña affected less than 1% for the whole record.

Including ENSO in the forecasting methods and in the evaluation of the wind resource is of great importance in most of the analyzed sites. The techniques for wind and production forecasting that are currently used by the operators of the electrical systems and in the literature, do not explicitly incorporate the phenomena of La Niña and El Niño, which can cause an under- or overestimation of the energy production from the wind farms. The high sensitivity to ENSO in the valuing of the wind farms is mainly due to the long duration of the wind projects, which typically is set to at least 20 years, which means that they can be affected by this oscillation many times. For this reason, a prediction technique that includes ENSO and other climatic oscillations should be developed, to adequately evaluate the potential of the sites. However, in order for these prediction methods to include ENSO in the best possible way, a larger data register than the measurements which are typically used are required. This work presented a methodology to handle the problem of short measurements, but the effectiveness of this method is improved when having longer registers.

For short and medium term operation, it is important to know at what point the phenomena El Niño and La Niña will occur, as well as their intensity. This work estimates the impact that different intensities of ENSO will have on the wind energy production, which allows for a more accurate estimation of the energy production in the following month. This is possible due to the fact that the ONI index has a certain level of inertia, which means that there are no abrupt changes from month to month, since this index is related to the temperature of the ocean. This level of predictability can be a tool for the operators of the electrical system to improve their planning of the following months. In the same way, this increased predictability can be utilized in the contracts, by adding clauses that include ENSO as an important factor. To achieve this, a mechanism should be determined to avoid that any of the parts assume risk inefficiently. This could for example be to set a lower price on the extra energy due to an event of La Niña. This analysis of ENSO can be extended to a higher resolution (for example weekly) to possibly identify the variations in the short term production due to ENSO. This level of resolution in the prediction could make it possible to have a larger flexibility in the operation of the system and in the supply contracts.

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References

[1] CNE, Capacidad instalada de en Chile, 2015, p. 1. http://www.cne.cl/estadisticas/energia/electricidad (Accessed 20 December 2015).
[2] CDEC SIC, Operación Real 2015, 2015. http://www.cdecsic.cl/ (Accessed 20 December 2015).
[3] CDEC SING, Resumen Ejecutivo de la Operación Año 2015, 2015. http://cdec2.cdec-sing.cl/ (Accessed 20 December 2015).
[4] B.D. Hamlington, P.E. Hamlington, S.G. Collins, S.R. Alexander, K.-Y. Kim, Effects of climate oscillations on wind resource variability in the United States, Geophys. Res. Lett. 42 (2015) 145–152, http://dx.doi.org/10.1002/2014GL062370.
[5] J.A. Carta, S. Velázquez, P. Cabrera, A review of measure-correlate-predict (MCP) methods used to estimate long-term wind characteristics at a target site, Renew. Sustain. Energy Rev. 27 (2013) 362–400, http://dx.doi.org/10.1016/j.rser.2013.07.004.

[6] GRID-Arendal, Climate Impacts of El Nino Phenomenon in Latin America and the Caribbean, 2003. http://www.grida.no/publications/vg/lac/page/2753.aspx (Accessed 22 December 2015).
[7] The Word Bank, World DataBank, 2012. http://databank.worldbank.org/data/reports.aspx?source=2&type=metadata&series=EG.ELC.HYRO.ZS (Accessed 20 December 2015).
[8] F. Fortes Westin, M.A. Dos Santos, I. Duran Martins, Hydropower expansion and analysis of the use of strategic and integrated environmental assessment tools in Brazil, Renew. Sustain. Energy Rev. 37 (2014) 750–761, http://dx.doi.org/10.1016/j.rser.2014.04.071.
[9] G. Poveda, D.M. Álvarez, Ó.A. Rueda, Hydro-climatic variability over the Andes of Colombia associated with ENSO: a review of climatic processes and their impact on one of the Earth's most important biodiversity hotspots, Clim. Dyn. 36 (2011) 2233–2249, http://dx.doi.org/10.1007/s00382-010-0931-y.
[10] S. Córdoba-Machado, R. Palomino-Lemus, S.R. Gámiz-Fortis, Y. Castro-Díez, M.J. Esteban-Parra, Assessing the impact of El Niño Modoki on seasonal precipitation in Colombia, Glob. Planet. Change 124 (2015) 41–61, http://dx.doi.org/10.1016/j.gloplacha.2014.11.003.
[11] N.E. Graham, K.P. Georgakakos, C. Vargas, M. Echevers, Simulating the value of El Niño forecasts for the Panama canal, Adv. Water Resour. 29 (2006) 1665–1677, http://dx.doi.org/10.1016/j.advwatres.2005.12.005.
[12] D.G. Palomino Cuya, L. Brandimarte, I. Popescu, J. Alterach, M. Peviani, A GIS-based assessment of maximum potential hydropower production in La Plata basin under global changes, Renew. Energy 50 (2013) 103–114, http://dx.doi.org/10.1016/j.renene.2012.06.019.
[13] J. Ronchail, R. Gallaire, ENSO and rainfall along the Zongo valley (Bolivia) from the Altiplano to the Amazon basin, Int. J. Climatol. 26 (2006) 1223–1236, http://dx.doi.org/10.1002/joc.1296.
[14] J.L.D.S. Soito, M.A.V. Freitas, Amazon and the expansion of hydropower in Brazil: vulnerability, impacts and possibilities for adaptation to global climate change, Renew. Sustain. Energy Rev. 15 (2011) 3165–3177, http://dx.doi.org/10.1016/j.rser.2011.04.006.
[15] K.-Y. Kim, G.R. North, J. Huang, EOFs of one-dimensional cyclostationary time series: computations, examples, and stochastic modeling, J. Atmos. Sci. 53 (1996) 1007–1017, http://dx.doi.org/10.1175/1520-0469(1996)053<1007:EOODCT>2.0.CO;2.
[16] K.-Y. Kim, G.R. North, EOFs of harmonizable cyclostationary processes, J. Atmos. Sci. 54 (1997) 2416–2427, http://dx.doi.org/10.1175/1520-0469(1997)054<2416:EOHCP>2.0.CO;2.
[17] B.D. Hamlington, R.R. Leben, K.Y. Kim, Improving sea level reconstructions using non-sea level measurements, J. Geophys. Res. Ocean. 117 (2012) 1–14, http://dx.doi.org/10.1029/2012JC008277.
[18] W.A. Gardner, A. Napolitano, L. Paura, Cyclostationarity: half a century of research, Signal Process. 86 (2006) 639–697, http://dx.doi.org/10.1016/j.sigpro.2005.06.016.
[19] N. Oses, Análisis espacial y temporal de la generación agregada de proyectos eólicos en los sistemas eléctricos en Chile, 2015.
[20] C. Santana, M. Falvey, M. Ibarra, M. García, Energías Renovables en Chile. El Potential Eólico, Solar e Hidroeléctrico de Arica a Chiloé, 2014, http://dx.doi.org/10.1073/pnas.0703993104.
[21] Ministerio de Energía, Explorador Eólico, Explor. Eólico, 2012. http://ernc.dgf.uchile.cl/Explorador/Eolico2/ (Accessed 20 December 2015).
[22] Ministerio de Energía, Campaña de medición del recurso Eólico y Solar, 2013. http://ernc.dgf.uchile.cl/mediciones/ (Accessed 20 December 2015).
[23] S.R. Yeo, K.Y. Kim, Global warming, low-frequency variability, and biennial oscillation: an attempt to understand the physical mechanisms driving major ENSO events, Clim. Dyn. 43 (2014) 771–786, http://dx.doi.org/10.1007/s00382-013-1862-1.
[24] B.D. Hamlington, R.R. Leben, R.S. Nerem, K.Y. Kim, The effect of signal-to-noise ratio on the study of sea level trends, J. Clim. 24 (2011) 1396–1408, http://dx.doi.org/10.1175/2010JCLI3531.1.
[25] B.D. Hamlington, R.R. Leben, R.S. Nerem, W. Han, K.-Y. Kim, Reconstructing sea level using cyclostationary empirical orthogonal functions, J. Geophys. Res. 116 (2011) 1–17, http://dx.doi.org/10.1029/2011JC007529.
[26] K.R. Briggs, ENSO Event Reproduction: a Comparison of an EOF vs. a Cyclostationary (CSEOF) Approach, vol. 63, 2006. http://diginole.lib.fsu.edu/cgi/viewcontent.cgi?article=3069&context=etd.
[27] K.-Y. Kim, C. Chung, On the evolution of the annual cycle in the tropical pacific, J. Clim. 14 (2001) 991–994, http://dx.doi.org/10.1175/1520-0442(2001)014<0991:OTEOTA>2.0.CO;2.
[28] K.E. Trenberth, D.P. Stepaniak, L. Smith, Interannual variability of patterns of atmospheric mass distribution, J. Clim. 18 (2005) 2812–2825, http://dx.doi.org/10.1175/JCLI3333.1.
[29] Z. Wu, E.K. Schneider, B.P. Kirtman, E.S. Sarachik, N.E. Huang, C.J. Tucker, The modulated annual cycle: an alternative reference frame for climate anomalies, Clim. Dyn. 31 (2008) 823–841, http://dx.doi.org/10.1007/s00382-008-0437-z.
[30] E. García-Bustamante, J.F. González-Rouco, P.A. Jiménez, J. Navarro, J.P. Montávez, A comparison of methodologies for monthly wind energy estimation, Wind Energy 12 (2009) 640–659, http://dx.doi.org/10.1002/we.315.
[31] I. Staffell, R. Green, How does wind farm performance decline with age? Renew. Energy 66 (2014) 775–786, http://dx.doi.org/10.1016/j.renene.2013.10.041.
[32] A.W.S. Truepower, Block Island Wind Farm Energy Production Estimate, 2012.
[33] A. Colmenar-Santos, S. Campiez-Romero, L. Enriquez-Garcia, C. Perez-Molina, Simplified analysis of the electric power losses for on-shore wind farms considering Weibull distribution parameters, Energies 7 (2014) 6856–6885, http://dx.doi.org/10.3390/en7116856.
[34] A. Colmenar-Santos, S. Campíñez-Romero, C. Pérez-Molina, F. Mur-Pérez, Repowering: an actual possibility for wind energy in Spain in a new scenario without feed-in-tariffs, Renew. Sustain. Energy Rev. 41 (2015) 319–337, http://dx.doi.org/10.1016/j.rser.2014.08.041.
[35] G. Caralis, D. Diakoulaki, P. Yang, Z. Gao, A. Zervos, K. Rados, Profitability of wind energy investments in China using a Monte Carlo approach for the treatment of uncertainties, Renew. Sustain. Energy Rev. 40 (2014) 224–236, http://dx.doi.org/10.1016/j.rser.2014.07.189.
[36] G. Xydis, A techno-economic and spatial analysis for the optimal planning of wind energy in Kythira island, Greece, Int. J. Prod. Econ. 146 (2013) 440–452, http://dx.doi.org/10.1016/j.ijpe.2013.02.013.
[37] S. Grassi, N. Chokani, R.S. Abhari, Large scale technical and economical assessment of wind energy potential with a GIS tool: case study Iowa, Energy Policy 45 (2012) 73–85, http://dx.doi.org/10.1016/j.enpol.2012.01.061.
[38] P.D. Friedman, Evaluating economic uncertainty of municipal wind turbine projects, Renew. Energy 35 (2010) 484–489, http://dx.doi.org/10.1016/j.renene.2009.07.012.
[39] SII, Impuesto a la Renta de Primera Categoría, 2015. http://www.sii.cl/aprenda_sobre_impuestos/impuestos/imp_directos.htm (Accessed 20 December 2015).
[40] A. Damodaran, Damodaran's Web Page, 2015. http://pages.stern.nyu.edu/~adamodar/ (Accessed 16 October 2015).
[41] D. Watts, C. Albornoz, A. Watson, Clean Development Mechanism (CDM) after the first commitment period: assessment of the world's portfolio and the role of Latin America, Renew. Sustain. Energy Rev. 41 (2015) 1176–1189, http://dx.doi.org/10.1016/j.rser.2014.07.146.
[42] Walter Short, Daniel J. Packey, Thomas Holt, A Manual for the Economic Evaluation of Energy Efficiency and Renewable Energy Technologies, 1995. http://www.nrel.gov/docs/legosti/old/5173.pdf.
[43] J. Kelleher, J.V. Ringwood, A computational tool for evaluating the economics of solar and wind microgeneration of electricity, Energy 34 (2009) 401–409, http://dx.doi.org/10.1016/j.energy.2008.10.009.
[44] A. Mostafaeipour, Economic evaluation of small wind turbine utilization in Kerman, Iran, Energy Convers. Manag. 73 (2013) 214–225, http://dx.doi.org/10.1016/j.enconman.2013.04.018.
[45] A. Mostafaeipour, M. Jadidi, K. Mohammadi, A. Sedaghat, An analysis of wind energy potential and economic evaluation in Zahedan, Iran, Renew. Sustain. Energy Rev. 30 (2014) 641–650, http://dx.doi.org/10.1016/j.rser.2013.11.016.
[46] M. Nedaei, E. Assareh, M. Biglari, An extensive evaluation of wind resource using new methods and strategies for development and utilizing wind power in Mah-shahr station in Iran, Energy Convers. Manag. 81 (2014) 475–503, http://dx.doi.org/10.1016/j.enconman.2014.02.025.
[47] V. Gass, F. Strauss, J. Schmidt, E. Schmid, Assessing the effect of wind power uncertainty on profitability, Renew. Sustain. Energy Rev. 15 (2011) 2677–2683, http://dx.doi.org/10.1016/j.rser.2011.01.024.
[48] K. Harijan, M.A. Uqaili, M. Memon, U.K. Mirza, Assessment of centralized grid connected wind power cost in coastal area of Pakistan, Renew. Energy 34 (2009) 369–373, http://dx.doi.org/10.1016/j.renene.2008.05.001.
[49] O.S. Ohunakin, O.O. Akinnawonu, Assessment of wind energy potential and the economics of wind power generation in Jos, Plateau State, Nigeria, Energy Sustain. Dev. 16 (2012) 78–83, http://dx.doi.org/10.1016/j.esd.2011.10.004.
[50] K. Mohammadi, A. Mostafaeipour, Economic feasibility of developing wind turbines in Aligoodarz, Iran, Energy Convers. Manag. 76 (2013) 645–653, http://dx.doi.org/10.1016/j.enconman.2013.06.053.
[51] F. Kanyako, I. Janajreh, Implementation and economical study of HAWT under different wind scenarios, Sustain. Cities Soc. 15 (2015) 153–160, http://dx.doi.org/10.1016/j.scs.2014.11.002.
[52] J.K. Kaldellis, T.J. Gavras, The economic viability of commercial wind plants in Greece. A complete sensitivity analysis, Energy Policy 28 (2000) 509–517, http://dx.doi.org/10.1016/S0301-4215(00)00039-2.
[53] National Weather Services, Climate Prediccion Center, 2015. http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml (Accessed 10 December 2015).
[54] M.H. González, C.S. Vera, On the interannual wintertime rainfall variability in the Southern Andes, Int. J. Climatol. 30 (2010) 643–657, http://dx.doi.org/10.1002/joc.1910.
[55] R.D. Garreaud, M. Vuille, R. Compagnucci, J. Marengo, Present-day south American climate, Palaeogeogr. Palaeoclimatol. Palaeoecol. 281 (2009) 180–195, http://dx.doi.org/10.1016/j.palaeo.2007.10.032.
[56] FAO, El Niño: Preparedness and Response Situation Report – March 2016, 2016. http://www.fao.org/emergencies/resources/documents/resources-detail/en/c/389344/ (Accessed 15 June 2016).
[57] F. Fazelpour, N. Soltani, S. Soltani, M.A. Rosen, Assessment of wind energy potential and economics in the north-western Iranian cities of Tabriz and Ardabil, Renew. Sustain. Energy Rev. ISSN: 1364-0321 45 (May 2015) 87–99, http://dx.doi.org/10.1016/j.rser.2015.01.045.
[58] J. Schallenberg-Rodríguez, J. Notario-del Pino, Evaluation of on-shore wind techno-economical potential in regions and islands, Appl. Energy. ISSN: 0306-2619 124 (1) (July 2014) 117–129, http://dx.doi.org/10.1016/j.apenergy.2014.02.050.
[59] J. Schallenberg-Rodriguez, A methodological review to estimate techno-economical wind energy production, Renew. Sustain. Energy Rev. ISSN: 1364-

0321 21 (May 2013) 272–287, http://dx.doi.org/10.1016/j.rser.2012.12.032.

[60] S. Diaf, G. Notton, Evaluation of electricity generation and energy cost of wind energy conversion systems in southern Algeria, Renew. Sustain. Energy Rev. ISSN: 1364-0321 23 (July 2013) 379–390, http://dx.doi.org/10.1016/j.rser.2013.03.002.

[61] S. Rehman, A. Ahmad, L.M. Al-Hadhrami, Development and economic assessment of a grid connected 20 MW installed capacity wind farm, Renew. Sustain. Energy Rev. ISSN: 1364-0321 15 (1) (January 2011) 833–838, http://dx.doi.org/10.1016/j.rser.2010.09.005.

[62] S. Rehman, T.O. Halawani, M. Mohandes, Wind power cost assessment at twenty locations in the kingdom of Saudi Arabia, Renew. Energy. ISSN: 0960-1481 28 (4) (April 2003) 573–583, http://dx.doi.org/10.1016/S0960-1481(02)00063-0.

[63] M.S. Adaramola, S.S. Paul, S.O. Oyedepo, Assessment of electricity generation and energy cost of wind energy conversion systems in north-central Nigeria, Energy Convers. Manag. ISSN: 0196-8904 52 (12) (November–December 2011) 3363–3368, http://dx.doi.org/10.1016/j.enconman.2011.07.007.

[64] M. Gökçek, M. Serdar Genç, Evaluation of electricity generation and energy cost of wind energy conversion systems (WECSs) in Central Turkey, Appl. Energy. ISSN: 0306-2619 86 (12) (December 2009) 2731–2739, http://dx.doi.org/10.1016/j.apenergy.2009.03.025.

[65] A.-H. Marafia, H.A. Ashour, Economics of off-shore/on-shore wind energy systems in Qatar, Renew. Energy. ISSN: 0960-1481 28 (12) (October 2003) 1953–1963, http://dx.doi.org/10.1016/S0960-1481(03)00060-0.

[66] M. Hoogwijk, B. Vries, W. Turkenburg, Assessment of the global and regional geographical, technical and economic potential of onshore wind energy, Energy Econ. ISSN: 0140-9883 26 (5) (September 2004) 889–919, http://dx.doi.org/10.1016/j.eneco.2004.04.016.