PONTIFICIA UNIVERSIDAD CATOLICA DE CHILE

ESCUELA DE INGENIERIA

EFFECT OF CLIMATE CHANGE ON WIND SPEED AND ITS IMPACT ON OPTIMAL POWER SYSTEM EXPANSION PLANNING: THE CASE OF CHILE

CATALINA ROSENDE JÜRGENSEN

Thesis submitted to the Office of Research and Graduate Studies in partial fulfillment of the requirements for the Degree of Master of Science in Engineering

Advisor:
ENZO SAUMA

Santiago de Chile, September, 2017

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A mi madre y su apoyo incondicional

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RESUMEN

Durante los últimos años, el término cambio climático ha sido escuchado más y más recurrentemente y se ha comenzado a estudiar lo que implicaría y cómo prepararse para esto, dado que, al conllevar cambios en el clima, podría afectar la generación energética entre otros efectos.

Los primeros lugares donde fueron instalados las plantas eólicas en Chile no fueron los mejores debido a falta de datos y de estudios (Watts, Oses, Perez. 2016). Dada la topografía de Chile y sus zonas de valles, montañas y costas se ha dicho que Chile es el segundo país con mayor potencial eólico en Sudamérica y el Caribe estimado en 40.000MW (Santana, Falvey, Ibarra, Garcia. 2014). Se dice también que, de escogerse los mejores proyectos eólicos futuros en el mediano plazo, estos podrían tener en promedio 37.9% de factor de planta e incluso en el peor escenario tendría un factor de 25.2% (Watts, Oses, Perez, 2016) lo que es positivo.

Dada la gran variabilidad del viento en espacios cortos de tiempo es necesario hacer un análisis tanto interestacional como interhorario. Dado esto, a continuación, se planteará un estudio con ese fin, para ver correlaciones entre distintos tipos de energías renovables no convencionales, distintas velocidades esperadas del viento en distintos escenarios de gases de efecto invernadero y se planteará un modelo de optimización para resolver en qué partes de Chile y en qué años convendría invertir en distintos tipos de ERNC. Se concluirá que el viento tendrá una relevancia fundamental en la matriz energética chilena y que el cambio climático incorporado a la velocidad del viento también afectará la generación en otras tecnologías de energías renovables.

Palabras Claves: Cambio climático, Economía del sistema eléctrico; Planificación de la expansión del sistema eléctrico; Generación de energía eólica

ABSTRACT

This study assesses the changes in investment decisions regarding power generation and transmission that occur when the effects of climate change on wind speed are captured in the decision model. Considering an 85-year period (2016-2101), we use a Mixed-Integer Linear Program (MILP) model to analyze the optimal investments in diverse types of power generation technologies, throughout the years and geographical locations. The optimization model minimizes the total (investment and operational) costs of the power system subject to several technical and economical constraints. We implement our model using the main Chilean power system. We compare two scenarios: one assuming that climate change affects wind speeds and hence wind farm capacity factors and the other assuming it does not. Our results reveal that, when taking into account the impact of climate change on wind speed, the optimal power generation and transmission expansion plan is significantly different than when ignoring this effect. The variation of wind speed affects not only wind power investments, but also other-technology generation investments. In particular, investments in solar and hydropower generation plants are higher (measured in MW installed) than investments when we ignore the effects of climate change; and investments in biomass, diesel, and natural gas technologies are lower. We perform sensitivity analyses, changing investment limits and the discount rate, to check for the robustness of our results.

Keywords: Climate Change; Power system economics; Power system expansion planning; Wind power generation

JEL Classification: L11, L94, Q42, Q54

1. Introduction

Climate change awareness has increased worldwide. Scientists have studied how to mitigate climate change and how to be prepared for the changes. In the power sector, scholars have studied how changes in the climate could affect energy development, especially considering renewable energy sources (RES) technologies for power generation. From a planning and operational perspective, one of the most challenging aspects of wind power is its variability (Cradden et al., 2015). Changes in wind speed, within the interval from 6m/s to 10m/s, may be the difference between a profitable or a non-profitable wind power plant (Harrison et al., 2008). Thus, estimating wind variability and considering these estimations in the evaluation of energy projects is crucial, especially in this climate change era.

Using an optimization model, this work assesses the changes in the optimal power system expansion plan when considering and ignoring the effects of climate change on wind speed. In particular, we consider the changes in technology, magnitude, location, and timing of power transmission and generation investments. In doing this, we consider two scenarios. The first one assumes that the capacity factors of RES power plants may be critically affected by climate change. It therefore incorporates the effects of climate change on wind speed. The second scenario assumes that these capacity factors stay constant. Simulation outcomes of both cases are compared in the case of the main Chilean network to assess differences regarding investments in power generation and transmission.

Some authors (Munoz et al., 2017) have studied how climate change affects hydropower production, but they generally ignore the effects on wind power or the correlations among the impacts. Thus, before assessing the impact of climate change on wind power production, it is interesting to explore the correlations among the power production for different RES technologies.

Using three years of hourly generation data from solar, hydroelectric (reservoir and run-of-river) and wind energy generators located in the North, Center and South of Chile, we examine correlations among power generation of diverse types of RES technologies. We then use inter- seasonal and inter-hour measures of wind speeds to study how wind capacity factors may change in different scenarios of greenhouse gas emissions in different years. Finally, we use all this information to assess the changes in the optimal power system expansion plan when considering and ignoring the effects of climate change on wind speed.

The rest of this article is organized as follows. Section 2 describes correlations between power generation of different RES (i.e., wind, run-of-river hydro, reservoir hydro, and solar). Section 3 discusses the evolution of wind speed in different scenarios of greenhouse gas emissions and shows a spatial and temporal analysis of changes in the wind speed in different cases. Section 4 presents an optimization model for the expansion of the electrical system in Chile for two cases: one that includes alterations in wind speed due to climate change and other that assumes constant capacity factors for wind power generation. Section 5 explains the data we used for the model implementation in the case of the main Chilean network. Section 6 shows the simulation results and their discussion. In this section, we also perform sensitivity analyses to check for the robustness of the results. Section 7 concludes the paper.

2. Correlations among RES productions in Chile

One of the many countries that have become progressively aware of environmental issues is Chile. The country must satisfy the increasing demand of energy, whilst complying with the conditions of a developed country. According to the Ministry of Energy, electricity consumption between 1990 and 2013 grew by 319.1%. An average annual increase of 2.7% in energy demand is predicted until 2025, and 2% thereafter (CDEC-SIC, 2017). Chile has one of the highest per capita carbon dioxide emission rates amongst countries in Latin America and the Mercosur (Mundaca, 2012). It faces the challenge of creating an effective and ambitious energy expansion, through diverse generation technologies, including RES such as wind, solar, and hydro power.

At the global level, wind power has led recent RES investments to mitigate climate change. Wind now commands a significant share of the world's electricity supply (global capacity stood at around 350 GW at the start of 2015 and is rising at 35% per year). Wind now comprises 13% of installed capacity in Europe (a greater share than nuclear power), and can provide more than the entire national demand in five countries, including Germany and Spain (Staffell and Pfenninger, 2016).

Given its topography (mountains, valleys, and coasts), Chile may well be considered the second country with the highest wind potential in South America and the Caribbean, estimated at 40,000MW (Santana et al., 2014). Some authors have stated that the best future wind projects in Chile could achieve an average capacity factor of 37.9%. In the worst scenario, it would reach a factor of 25.2% (Watts et al., 2016), a good prospect for wind generation. Watts and Jara (2010) have suggested that a viable option to reduce carbon emissions in the northern area of Chile is to encourage wind power generation. In addition, Garreaud and Falvey (2008) argue that coastal wind speeds in Chile will increase by 15% toward the end of the century, allowing more onshore and offshore wind projects to become feasible.

On the other hand, in a country as long and narrow as Chile (2.653 miles long and an average of 110 miles wide–from the Andes to the Pacific Ocean), in which different atmospheric conditions jointly occur, it is ambiguous whether RES generators along Chile could complement each other in diverse weather conditions.

In this section, we analyze the correlations among the power produced by solar, hydroelectric (reservoir and run-of-river) and wind power plants located in the Northern, Central and Southern parts of Chile. We use real-measured data from August 2013 to July 2016. The aim of this exercise is to check that correlations are not significant in the same block time and season, meaning that the effect of climate change on wind generation must be considered independently of its effect on hydro generation when analyzing the power system expansion planning.

The Chilean National Electric Coordinator provides data for most RES generators in Chile. This institution coordinates the operation of the power installations at the generation and transmission levels. The data include hourly power generation (for the three years mentioned before) from wind, reservoir hydro, run-of-river hydro, and solar power plants throughout Chile. We aggregated the data into 10 groups, according to RES technology and zone (i.e., Run-of-river North/Center/South, Reservoir Center/South, Wind North/Center/South, Solar North/Center). There is no reservoir hydropower generation in the North of Chile (where the dry, arid desert is located) and no solar energy generation in the South region (where solar radiation is limited and there is a short summer season).

Data were analyzed on a per-semester basis, considering "summer" periods (from October to March) and "winter" periods (from April to September). We studied three summer period 2013/14, 2014/2015 and 2015/2016. We also consider three winter periods, which were built including data from August and September of the previous year in the winter period starting in April, in order to consider all the information contained in the available data.[1]

[1] In order to include all the information contained in the available data (August 2013-July 2016), we included data for period August 2013 and September 2013 in the winter period starting in April 2014. Hence, the first winter period studied has information measured from April 2014 to July 2014 plus August 2013 and September 2013. The two other winter

For every semester, correlations are calculated using hourly data. Figure 1 graphically shows the correlation levels in the case of the three winter periods studied. On the right side of every matrix, there is a color scale representing the level of the corresponding correlation value. We use the same scale in all matrices. The size of each dot in the matrix depends on the absolute value of the correlation between two specific RES-zone combinations.

Correlation results for the first winter period are shown in the upper matrix. A surprisingly significant positive correlation is observed between solar generation in the North zone and run-of- river hydro generation in the same zone. This suggests that solar intensity and run-of-river intensity may be related. A partial explanation is that intense sunshine melts the snow in the Andes Mountains, increasing the flow in the rivers. However, there is little snow in the mountains of the north of Chile. Rain is very scarce in the north too (e.g., considering the 900 miles between Arica and La Serena, the total rainfall in 2016 was 10.9 mm; DGAC Chile, 2016), making correlations insufficiently representative. In this upper matrix, we also observe a few minor negative correlations, as well as some slightly positive correlations, particularly between same zones and between reservoir hydro and run-of-river hydro.

Results for the second winter period analyzed are presented in the middle matrix of Figure 1. Again, there is a significant positive correlation between solar generation in the North and run- of-river hydro generation in the North. We also observe a positive correlation between the energy generated by reservoir and run-of-river hydro power in the central zone, which makes sense due to the influence of rain patterns. Regarding wind power plants, in this period we observe that wind generation in the North is positively correlated both with run-of-river generation and with solar generation; while wind generation in the Center is negatively correlated both with run-of-river generation and reservoir hydro generation. This is partially explained by the fact that, in the central part of Chile, wind usually comes before rain and not while raining.

The lower matrix of Figure 1 shows correlation results for the third winter period studied (April to July of 2016 plus August and September of 2015). Several hydro plants are positively correlated to each other. There are no significant negative correlations in this period. Wind generation in the South is positively correlated with wind generation in the Center; and solar generation in the North is positively correlated with solar generation in the

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periods were built in the same manner.

Center. We also observe that the previously-observed positive correlation between solar generation in the North zone and run-of-river hydro generation in the same zone totally disappears.

Summarizing results in these three winter periods, the only recurring correlations are among hydro sources.[2] Regarding other correlations, in two of the three winter periods, positive correlations are found in the North zone between solar and run-of-river hydro generation. Generally speaking, there is no strong pattern that would suggest the existence of a relationship among the different types of RES generation.

Summer periods' results are shown in Figure 2. The upper matrix shows correlation results considering the hourly generation registered between October of 2013 and March of 2014. During this period, solar generation is included only in the North zone because it was zero in the other regions. As in winter periods, there are slight positive correlations among hydro generation technologies. Results also suggest a negative correlation in the South between wind generation and run-of-river hydro generation, meaning that wind is strong when rainfall is scarce, and vice versa.[3] In the North zone, there is a positive correlation between solar and run-of-river hydro generation. A partial explanation is that, as mentioned before, intense sunshine melts the snow in the Andes Mountains. However, it is also important to highlight that the extreme scarcity of rain in the north of Chile may also explain these results.

The middle matrix of Figure 2 describes correlations for the period from October of 2014 to March of 2015. Again, there is a strong positive correlation between solar and run-of-river hydro generation in the North. There is also a slightly positive correlation between run-of-river hydro generation in the South and reservoir hydro in the central part of Chile.

The bottom matrix of Figure 2 illustrates correlations obtained with data from October of 2015 to March of 2016. As in the other periods, generation from diverse hydro plants are correlated. There are other positive correlations, particularly between solar generation in the North and in the Center.

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[2] Naturally, there are some exceptions, which are related to the fact that, in general, run-of-river hydro plants are not able to choose the time for generation, while reservoir hydro plants make a strategic management of water, saving sometimes water to satisfy future demand.

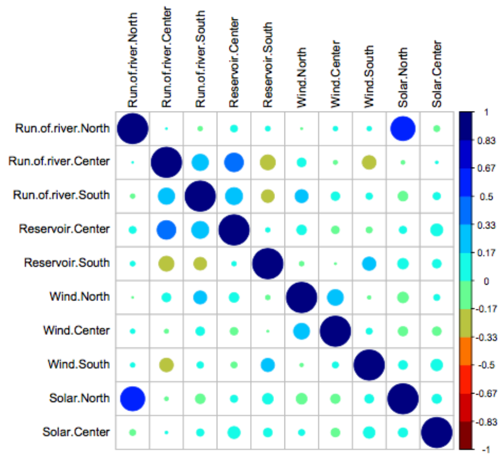
[3] In the south of Chile, it is relatively common having strong winds in the hours or days before big rainfalls; and once the rain starts, the wind diminishes notably.

Succinctly, the three summer periods analyzed do not show a strong pattern that would suggest that wind generation is correlated with power from other RES technologies.

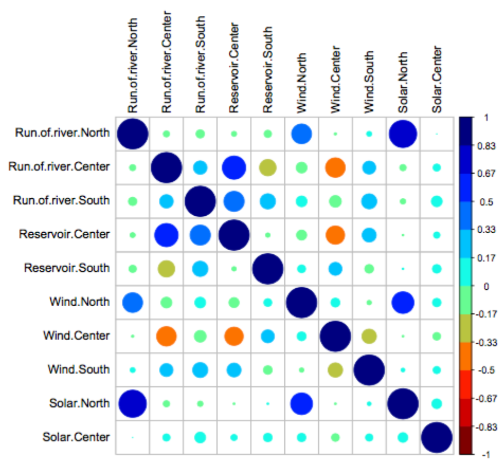
Therefore, considering the results in winter and summer periods, we cannot observe evidence of a correlation between wind power generation and power production from other RES.

Accordingly, we can argue that the impact of climate change on wind power production can credibly be studied independently from its impact on other RES.

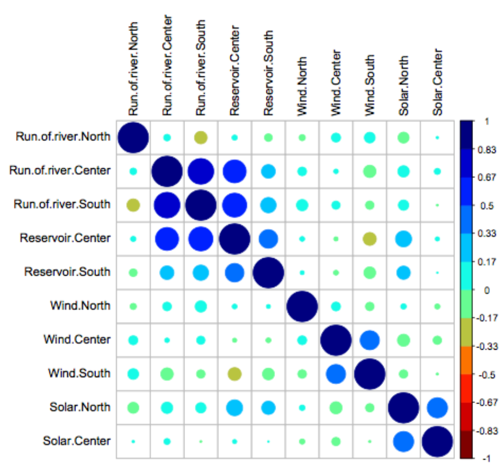
Figure 12: Correlations of hourly power generation among RES types in Winter Periods



Correlations between the hourly generation from April to October 2013-2014

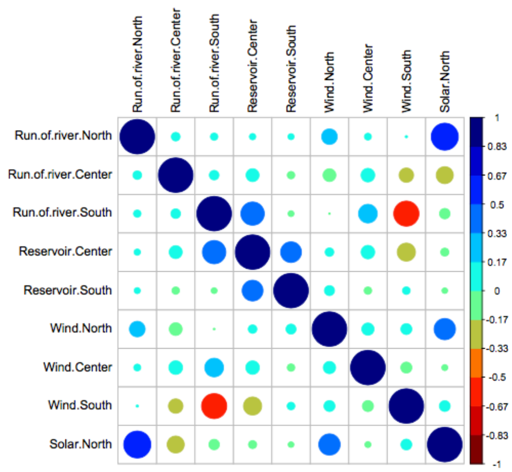


Correlations between the hourly generation from April to October 2014-2015

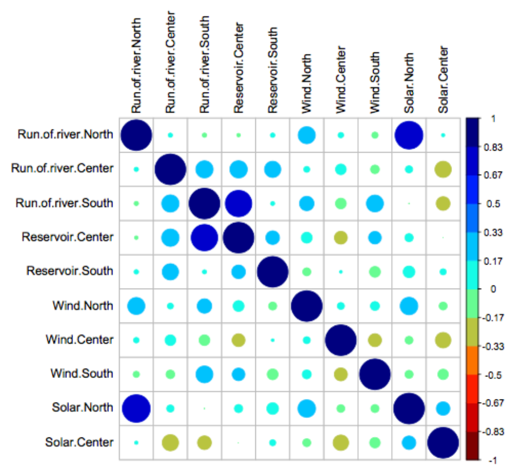


Correlations between the hourly generation from April to October 2015-2016

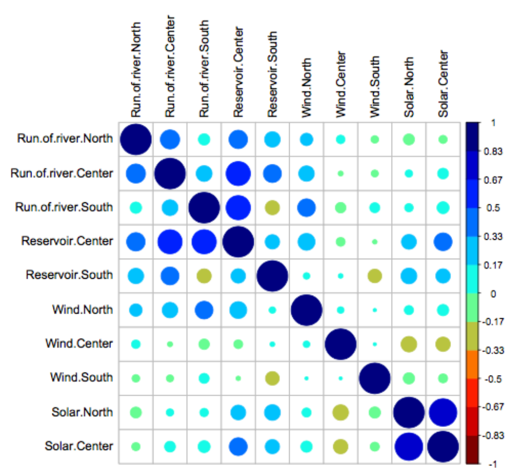
Figure 13: Correlations of hourly power generation among RES types in Summer periods



Correlations between the hourly generation from October to April 2013-2014



Correlations between the hourly generation from October to April 2014-2015



Correlations between the hourly generation from October to April 2015-2016

3. Projected wind speed evolution under different scenarios of greenhouse gas concentrations

In this section, we present an analysis of the expected changes in wind speed in Chile for the coming decades. The data was provided by the National Center for Atmospheric Research (NCAR).[4]

We study future wind speed evolutions for different timing and locations along Chile. The specific locations are chosen according to the nodes that the Chilean Ministry of Energy has established in its long-term strategic plan (PELP, from Spanish) as strategic energy transmission points. The rationale for assuming this is that it is likely that power stations near these strategic points will have to pay relatively low transmission costs to inject their energy into the system, compared to power stations that are far from strategic nodes.

We report wind speed projections for the years 2030, 2050, and 2100, under different scenarios of greenhouse gas concentrations. These scenarios are called Representative Concentration Pathways (RCP). We consider three RCPs: RCP 4.5, RCP 6.0, and RCP 8.5. The first two are stable scenarios, respectively involving a CO2 level of 528 parts per million (ppm) and 670 ppm by year 2100. The third scenario, RCP 8.5 represents a higher level of greenhouse gas emissions and involves a concentration of CO2 of 936 ppm by year 2100 (IPCC, 2013).

To extract wind speed data from the NCAR database, we searched the data panel for the longitude and latitude of every location considered in this study. For every selected location and year, we extracted the wind speed data for four days of the year. The days chosen arbitrarily were: January 1st, April 1st, July 1st, and October 1st. For each of these days we gathered the wind speed projections for four different specific hours of the day: 6:00 12:00, 18:00, and 24:00. The four wind projections considered for specific days are symbolized with numbers 1 to 4 following the abbreviation of the month considered. For instance, for the chosen day in January (January 1st), each of the four hourly measures are expressed as Jan1, Jan2, Jan3 and Jan4. Hence, Jan1 refers to the projection of 6am on January 1st; Jan2 refers to the noon projection on January 1st; and so forth. The same notation is used for April

[4] This institution is a U.S. federally funded research and development center, managed by the nonprofit University Corporation for Atmospheric Research (UCAR) and funded by the National Science Foundation (NSF).

1st, July 1st and October 1st. Wind projections in the database are made at 125 meters from ground level.

The analyzed sites are 10 nodes of the *Sistema Interconectado del Norte Grande* (SING),[5] the interconnected system that serves the farthest northern area of Chile, and 19 nodes of the *Sistema Interconectado Central* (SIC),[6] the central interconnected system of Chile. These are the two biggest transmission systems in Chile.

Appendix 1[7] contains Graphs 1-4, which show the average wind speeds for every group of nodes [SING, SIC(1), SIC(2), and SIC(3), respectively]. The different colors reflect the scenarios, and the different shapes reflect the observed years (2030, 2050, and 2100). Specifically, green represents scenario RCP 4.5, orange RCP 6.0, and blue RCP 8.5. Shapes represent years: circles refer to year 2030, squares to 2050 and triangles represent year 2100.

Graph 1 shows data for SING nodes. Comparing year-scenario combinations for any particular node, wind speeds differ by almost 2 m/s. The year-scenario combination that is projected to have the highest wind speed in all SING locations is the RCP 8.5 scenario in year 2050. In some areas, the second highest projected wind speeds are found in year 2100 instead of 2050, but also in the RCP 8.5 scenario. However, in Changos, Kimal, Laberinto and Encuentro the second-best situation in terms of wind speed is in the RCP 4.5 scenario in year 2100. This combination of year, RCP, and location is favorable for wind generation and also for the environment due to a healthier air composition.

Graph 2 shows data for SIC(1), the northern segment of the central interconnected system. Here the highest wind speeds are found in the RCP 8.5 scenario.

Graph 3 shows that, in most SIC(2) locations, the highest wind speeds occur in an RCP 6.0 scenario in year 2030 (e.g. in Alto Jahuel, Candelaria, Cerro Navia, and Rapel), and that,

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[5] The SING nodes are: Atacama, Changos, Collahuasi, Cóndores, Encuentro, Kimal, Laberinto, Lagunas, Parinacota and Tarapacá.

[6] For analytical convenience, we analyze the SIC nodes in three different groups, separating them mainly in a geographical way, from North to South. SIC(1) includes the nodes that are geographically in the northern part of the SIC system: Cardones, Cumbres, Las Palmas, Pan de Azúcar, Paposo and Punta Colorada. SIC(2) follows, with Alto Jahuel, Candelaria, Cerro Navia, Los Vilos, Polpaico and Rapel. SIC(3) includes the most southern area of the sample: Ancoa, Cautín, Chiloé, Mulchén, Puerto Montt, Rahue and Valdivia.

[7] Given the large amount of figures in this section, we prefer to show some of them in the appendix.

within this scenario, wind speeds will decrease by an average of 1m/s from 2030 to 2100. The same happens within this scenario at the SIC(3) nodes, as shown in Graph 4 (e.g. Ancoa, Cautín, Mulchén, Rahue, and Valdivia). Changes in wind speed affect the capacity factor, the stability and the effectiveness of generation, which adds vulnerability to the system. In scenarios RCP 4.5 and RCP 8.5, wind speeds are in general more stable along the years. This imparts more stability to the system as well.

To clearly appreciate the effects that changes in RCP perpetrate in different scenarios, we repeated the previous analyses, this time keeping the year constant (specifically year 2030) and changing only gas concentrations. SIC nodes were segmented with the same criteria as above. Hence, there are four groups of nodes and 3 scenarios for each group; consequently 12 graphs. Appendix 2 displays these graphs in three rows and four columns. Every row contains a different RCP scenario (e.g., the top row displays four graphs for RCP 4.5) and every column represents a different group of nodes [SING, SIC(1), SIC(2), and SIC(3)]. The first column in Appendix 2 shows results for the SING nodes within year 2030. Roughly speaking, wind speed slows down if RCP is 6.0 instead of 4.5. This holds for all nodes in this group, and the change for some of them is dramatic, such as in Parinacota, where wind speeds fall from an annual average of 7.45m/s to an annual average of 5.8m/s from scenario RCP 4.5 to RCP 6.0. On the contrary, if RCP is 8.5 instead of 6.0, wind speeds increase in all the segments.

Interestingly, there seems to be a pattern in the changes in wind speed according to time blocks and seasons within the different scenarios. For the SING area, the highest speeds are in January, independently of the RCP. The second highest speeds of the year are, in general, in October. The average annual wind speed for all the scenarios and block times in the SING area is 6.33m/s.

The second column in Appendix 2 displays three graphs (one for each RCP) for wind speeds in the SIC(1) nodes. Depending on the season of the year, there are significant changes in wind among scenarios. Particularly, January and July exhibit changes in wind speed of up to 2m/s between RCPs. Amidst different RCP scenarios, the annual average wind speed for all SIC(1) nodes has maximum variations of about 1m/s. The biggest change occurs in Punta Colorada, where the annual average speed moves from 4.83m/s in RCP 6.0 to 5.86m/s, in RCP 8.5. This implies that a rise in greenhouse gases could bring an increase in wind speeds of 1.03m/s in the Punta Colorada area. In 2030, the total average speed in SIC(1), considering all scenarios and time blocks, is 5.36m/s.

Repeating the above analysis for the SIC(2) nodes, displayed in the three graphs standing in the third column of the same figure, we observe that -as in the case of the SING nodes- average annual wind speeds increase when moving from the RCP 4.5 scenario to RCP 6.0, and decrease when the RCP scenario is changed from 8.5 to 6.0. This holds for all nodes in the SIC(2) segment. The only exception is Los Vilos, where the average wind speed increases slightly when moving from RCP 6.0 to RCP 8.5.

The last column of graphs in this figure displays data from the southern nodes, SIC(3). The highest wind speeds are in general in July, with the exception of Chiloe and Puerto Montt where highest speeds occur in January for both of the stable scenarios (RCP 4.5 and RCP 6.0). A particular phenomenon occurs under scenario 4.5 in Rahue, on July 1st, in the time block going from 18:00 to 24:00. In this case, the speed is triggered from 6m/s to more than 12m/s. This is an isolated weather event, maybe product of strong winds before a storm.

Of all the zones analyzed, the ones with the highest wind speeds, regardless of the gas concentration scenario, are almost always found in the SING areas. Every analyzed place in the SING is projected to have average annual speeds greater than 6m/s, with the exception of Atacama and Changos, which have slightly slower winds (5.85m/s). This confirms the idea that wind generation in the North will have good results in almost all areas and scenarios (Watts and Jara, 2010).

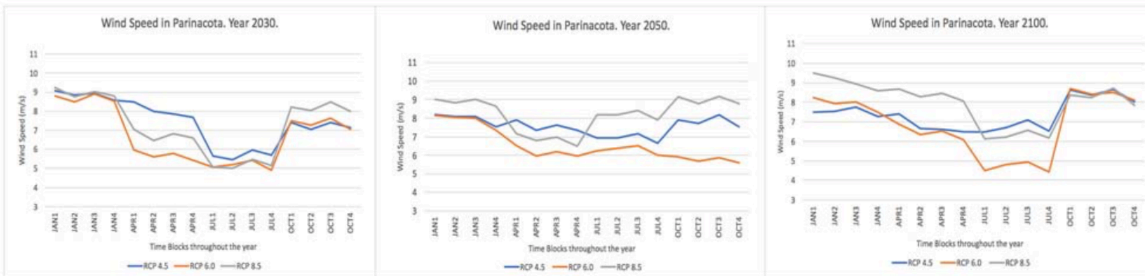
As for specific zones throughout Chile, the highest average speeds, regardless of the greenhouse gas scenarios, are in the southern island Chiloé (with an average of 7.12m/s), in the northern region of Tarapacá (with an average of 7.01m/s), in the southern city of Puerto Montt (with 6.71m/s), in Parinacota (with 6.62m/s), and in Collahuasi, Condores and Encuentro (which have wind speeds of approximately 6.5m/s). These average speeds would allow wind generation with an average capacity factor higher than 20%.

For every location and for each of the specified years (2030, 2050, and 2100), we calculate wind speed averages for the three analyzed RCP scenarios (RCP 4.5, 6.0, and 8.5). Appendix 3 displays these averages for every node for years 2030, 2050 and 2100. Every column is a different group of nodes and every row is a different year. In the first column, which represents averages for the SING system, it is noteworthy that between 2030 and 2050 speed increases by less than 0.5m/s for all nodes. From 2050 to 2100 speeds also rise at every point (by less than 0.4m/s), except for Cóndores, where they decrease by 0.1m/s. Hence, speeds in the farthest northern area of Chile are expected to be relatively stable. In terms of seasons, the data show that, over the years wind speed exhibits major increases in October, followed by April, but the greatest speeds are in January. In fact, the projections made for January average 8.25m/s across all the analyzed SING nodes, which is a suitable speed for wind generation. However, this speed average occurs only in January and it is not as favorable in April and July, when it averages approximately 5.5 m/s. It rebounds in October, averaging 7m/s, which is also a convenient scenario for wind power generation. The yearly averages for the SING nodes (first column of graphs in Appendix 3) are 6.32m/s in 2030, 6.68m/s in 2050 and 6.78m/s in 2100. The SING zones with the highest average speed for the three analyzed periods are Parinacota with an average speed of 7.33m/s and Cóndores, with an average of 6.88m/s. In column 2 [SIC(1) nodes], the speeds remain fairly constant over the years, excluding the case of Cumbres, Pan de Azúcar and Paposo in October 2100, where speeds rise by 1m/s. The annual average for each year in the SIC(1) areas is 5.36m/s in 2030, 5.45m/s in 2050 and 5.53m/s in 2100. Of the nodes in this set, the only ones with an average speed of 6m/s or more are Paposo and Cumbres. Column 3, [SIC(2) nodes], shows a stable situation during January over the years. In April speeds decrease 1m/s between 2030 and 2100. Speeds fall between 2030 and 2050 in all other nodes of this group, and decrease even more between 2050 and 2100. The only exception is Polpaico, where wind speeds are expected to increase 0.3m/s between 2030 and 2100. The biggest speed changes between 2030 and 2100 occur in Cerro Navia and Rapel, where speed averages fall 0.7m/s. Of the nodes considered in SIC(2), all average speeds are 5m/s or less.

Column 4 exhibits data for SIC(3), the southern zone of Chile. The January measurements reflect that, on average, wind speeds will decrease by 1.8m/s from 2030 to 2050, while the April data indicates stability around 5.2m/s. In July the average increases to 7.3m/s in 2030, but it falls to 6.6m/s in 2050, rising again in 2100 to an annual average of 7.01m/s. The highest speeds are always found in Chiloe with a total average of 6.84m/s for the 3 analyzed years. Between 2030 and 2050, winds reduce in all the nodes of this subset. In 2100 wind speeds increase, but by less than they had fallen before. The average speed of winds (for all years) in this column is 5.6m/s, with the highest velocities in 2030 averaging 5.9m/s.

For illustration, Figure 3 shows wind speed variations under different RCP scenarios for Parinacota, the specific area in the North of Chile where the highest wind speeds are projected.

Figure 14: Wind Speed in Parinacota in different years



We can observe that, in some cases, there are more than 3 m/s difference among scenarios. This can change the capacity factors of a wind power plant enormously. In general, the figure shows that the lowest wind speeds are in RCP 6.0. In year 2050 and 2100, most of the highest wind speeds are in RCP 8.5. There are big differences of wind speeds among diverse combinations of cases and years. This makes project evaluation difficult.

Considering all the analyzed nodes and periods, the highest average rates of wind speeds are almost always found in the North. As mentioned, the highest speeds are found in Parinacota, with an average of 7.3 m/s over the years, followed by Cóndores, Tarapaca and Chiloé, with an average of 6.8 m/s. All of the SING nodes have an average speed greater than 6m/s. As for the rest of the nodes, only Cumbres, Chiloé and Puerto Montt have an average speed greater than 6m/s throughout the years.

The best month-area combination for wind generation is in January in the SING area, with an average of 8.25 m/s. In the SIC(1) segment, it is in January also with an average of 6.06m/s, while in SIC(2) and SIC(3) it is during July, with an average of 6.28 m/s and 7 m/s, respectively.

The analyzed data invites deeper analysis regarding the convenience of installing a greater number of wind plants in the north of Chile and in the southern island Chiloé. On the other hand, it is necessary to study the actions that are being taken not only in Chile, but in the rest of the world, to have accurate forecasts of RCP scenarios, thus being able to make more informed decisions regarding the places where to install wind power plants to maximize generation.

4. Optimization model for the system expansion planning of the electrical system in Chile

In this section, we formulate an expansion planning model for the Chilean electrical system. The model is based on the formulation proposed by Munoz et al. (2013). As in (Munoz et al., 2013), our model minimizes total costs, composed of investment costs in power plants, transmission investment costs, and operational generation costs. Differently than in (Munoz et al., 2013), our model allows for power plants with capacity factors that vary over time. In the case of Chile, recent work suggests that wind speeds are expected to change favorably in many areas –due to climate change- hence augmenting capacity factors (Barton, 2013; Sailor et al., 2008). Another difference of our model is that, considering the economic investment possibilities of Chile, we set investment limits for each generation technology. We also account for changes over time in energy demand.

In this setting, the optimization question is how to satisfy the increasing Chilean energy demand, while minimizing costs. With data of the expecting demand and capacity factors for wind from 2016 to 2101, we run the model to identify the optimal timing and locations in which investment in transmission lines and in new power plants would result most cost-effective. The model is allowed to make investment decisions every five years between 2016 and 2101.

We compare two cases. Case 1 takes wind speed projections predicted by the National Center for Atmospheric Research (NCAR) and uses the Rayleigh distribution (Harrison et al., 2008) to transform the speeds into capacity factors, assuming turbines of 3MW of rated power with a diameter of 45 meters. In this way, we incorporate the possible effects of climate change on wind speed in different zones of Chile, in different seasons of the year, and on various hours of the day. We assume constant capacity factors in all other generation technologies. Case 2 assumes that climate change does not affect the speed or intensity of winds in Chile; ergo, all capacity factors remain constant –at their 2016 levels- throughout the periods considered. The model minimizes total system (investment and operating) costs, subject to a series of constraints: generation limits, nodal energy balances (DC approximation of Kirchhoff's Current Law), maximum power flow constraints, transmission line constraints (DC approximation of Kirchhoff's Voltage Law), and investment limits per technology per period. We ignore transmission losses as well as the possibility of energy curtailment.

Marginal costs of wind farms, as well as of solar and run-of-river hydro plants, are assumed to be zero. The model is formulated as follows.

$$Min \sum_{t\in T}\sum_{b\in B}\sum_{k\in K} CI_{b,k} y_{b,k,t}\delta^t + \sum_{t\in T}\sum_{l\in L}\sum_{s\in S} CC_l x_{l,s,t}\delta^t + \sum_{t\in T}\sum_{h\in H}\sum_{b\in B}\sum_{k\in K} MC_{b,k} g_{b,k,h,t}\delta^t \quad (1)$$

Subject to:

$$\sum_{t\in T} y_{b,k,t} \le Y^M_{b,k} \quad \forall b,k \quad (2)$$

$$\sum_{l\in L}\sum_{n\in S\cup C} f_{l,n,h,t} + \sum_{k\in K} g_{b,k,h,t} = D_{b,h,t} \quad \forall b,h,t \quad (3)$$

$$f_{l,c,h,t} - \gamma_l(\theta_{b,h,t} - \theta_{p,h,t}) = 0 \quad \forall (b,p)\in\Omega_l \quad \forall c\in C \quad \forall\, l,h,t \quad (4)$$

$$|f_{l,s,h,t} - \gamma_l(\theta_{b,h,t} - \theta_{p,h,t})| \le M(1 - \sum_{\tau\le t} x_{l,n,\tau}) \quad \forall (b,p)\in\Omega_l \quad \forall s\in S \quad \forall\, l,h,t \quad (5)$$

$$|f_{l,c,h,t}| \le F_{l,c} \quad \forall c \in C \quad \forall\, l,h,t \quad (6)$$

$$|f_{l,s,h,t}| \le F_{l,c} \sum_{\tau\le t} x_{l,n,\tau} \quad \forall s \in S \quad \forall\, l,h,t \quad (7)$$

$$g_{b,k,h,t} \le W_{b,k,h,t}\left(Y^0_{b,k} + \sum_{\tau\le t} y_{b,k,t}\right) \quad \forall\, b,k,h,t \quad (8)$$

$$\sum_{\tau\le t} x_{l,s,\tau} \le 1 \quad \forall l,s,t \quad (9)$$

$$\sum_{q\in Q}\sum_{h\in H}\sum_{b\in B} g_{b,q,h,t} \ge \alpha \sum_{k\in K}\sum_{h\in H}\sum_{b\in B} g_{b,k,h,t} \quad \forall t\in T \quad (10)$$

$$\sum_{b\in B} y_{b,k,t} \le IL_k \quad \forall t,k \quad (11)$$

$$|\theta_{b,h,t}| \le \frac{\pi}{2} \quad (12)$$

$$y_{b,k,t} \ge 0 \quad g_{b,k,h,t} \ge 0 \quad x_{l,s,t} \in \{0,1\} \quad (13)$$

The notation used here is explained next. B denotes the set of buses (or nodes, indexed by *b*), K the set of generation technologies (indexed by *k*), Q the subset of K consisting of renewable generation technologies (indexed by *q*), and L the set of lines (indexed by *l*). Ω_l represents the set (pair) of nodes connecting corridor *l*; C the set of circuits already built between one node and another (indexed by *c*); and S the set of candidate circuits to be built between two nodes (indexed by *s*). Indexed by *n* is the union of S and C. H is the set of hours per year (indexed by *h*), and *t* is the period that is being analyzed [with t= (Year-2016)/5+1); hence t=3 is year 2026, the third period evaluated, preceded by year 2021 (t=2)]. M is a big positive number.

The main decision variables of the model are $y_{b,k,t}$ (in MW) representing new generation investments, $x_{l,s,t}$ (dimensionless 0-1 variable) for transmission investments, and $g_{b,k,h,t}$ MW for generation; $f_{l,n,h,a}$ denotes the power flow (in MW) over corridor *l* and circuit *n*; $\theta_{b,h,a}$ (in radians) corresponds to the voltage phase-angle at bus *b*.

With respect to the parameters used in the model, new generation capacity of type *k* can be added to bus *b* at a capital cost $CI_{b,k}$ in \$/MW/yr. Regarding RES investments, we assume that capital costs decrease by 5% every period t (i.e., every 5 years). RES plants are operated at a marginal cost $MC_{b,k}$ \$/MWh. Capital cost of adding a new circuit to corridor *l* is CC_l. Parameter $Y_{b,k}^{0}$ is the existing generation capacity of type *k* at bus *b*; parameter $Y_{b,k}^{M}$ is the maximum generation capacity investment of type *k* allowed at bus *b*, and parameter $W_{b,k,h,t}$ is the capacity factor of generation of type *k* at bus *b* and hour *h*. Line capacities and susceptances are represented by parameters $F_{l,c}$ and $\gamma_{l,c}$, respectively.

Energy demand at bus *b* and hour *h* in year *t* is denoted as $D_{b,h,t}$. Demand increases over the years by the percentages determined in the Demand forecasting study published by the Chilean National Energy Commission, based on 2016 demand. The RES quota requirement is $\alpha = 0.25$, expressed as a fraction of the supplied energy. To avoid unrealistic results, we consider an investment limit for each generation technology, per period. This investment limit, denoted by IL_k, is fixed throughout the periods of the study, but differs between technologies.

Logical relationships are added to the constraint set so that generation and transmission capacities constructed in 1 year are also available in later years. Any specific transmission line can only be constructed once. The discount rate is δ.

5. Data for model implementation

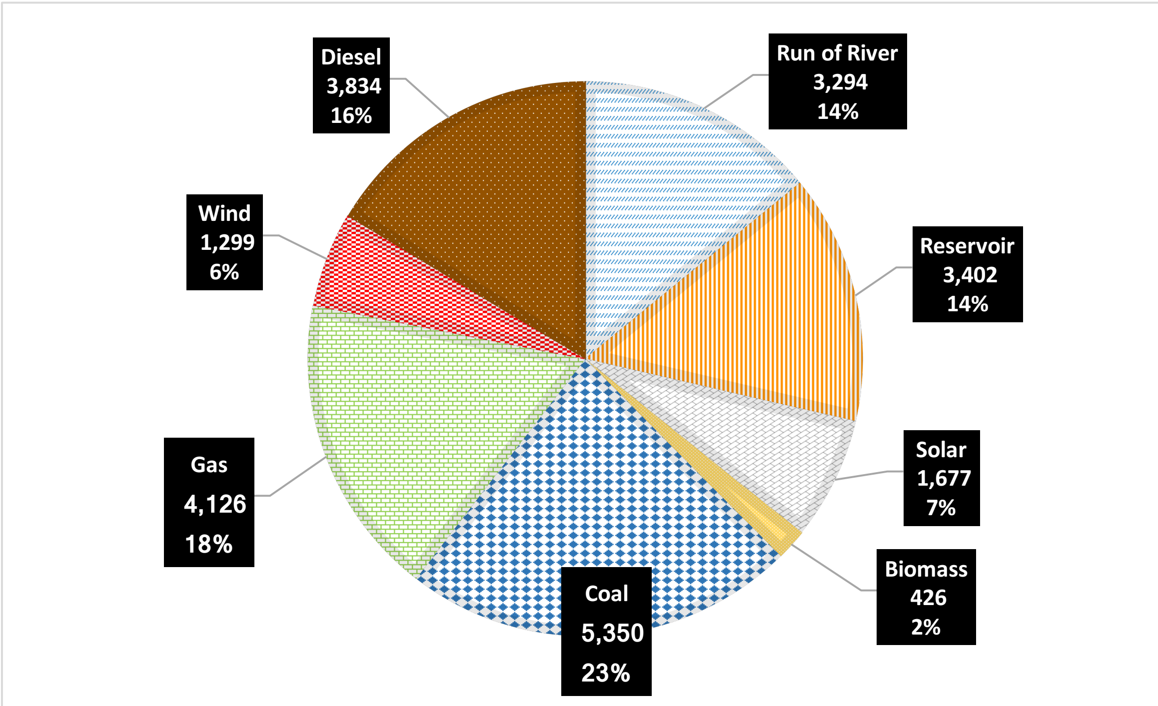
Information about transmission lines currently used in Chile, as well as the transmission lines that are in process of construction, and those that have construction approval, but have not begun to be built were taken from (CDEC-SIC, 2017), (CDEC-SING, 2017), (CNE, 2016a), and (CNE, 2016b). For every transmission line we obtained its maximum capacity (in MW) and its reactance. Information about current capacity of coal, diesel, natural gas, wind power, run-of-river hydro, reservoir hydro, and solar power plants in every zone, by type of generation technology, was also obtained from (CDEC-SIC, 2017) and (CDEC-SING, 2017).

We use the hourly generation obtained in section 3 for computing the initial (2016) capacity factor of wind farms (generation was measured every hour of the day and then it was compared to the maximum capacity of every power plant, calculating the factor capacity that every central had in a specific time block and on a specific day of the month). In every period (i.e., every five years) between 2016 and 2101, we incorporate changes in energy demand and in wind plant capacity factors. For each of these 18 5-year periods, we analyze four days, specifically, the first day of each of four different months: January, April, July, and October. In each of these days, we extract the measure at four specific times: 0:00, 6:00, 12:00, and 18:00. Hence a year will have 16 evaluated hour blocks, distributed in four months. This originates an inter-hour and inter-seasonal sample while avoiding averaging out wind variability. The discount rate assumed in this study is 2.715%.

The initial power matrix in year 2016 in Chile is presented in Figure 4 (amounts in MW). Wind represents only 6% of total generation. The sum of coal, diesel and gas generation is 57%. The Chilean Minister of Energy pursues the challenge of increasing the proportion of RES supply up to 70% by 2035.[8]

[8] Ministerio de Energía. "Energía 2050 Política Energética Chile". http://www.energia.gob.cl/sites/default/files/energia_2050_-_resumen_de_la_politica_energetica_de_chile.pdf

Figure 15: Power generation matrix (in MW) in Chile, 2016

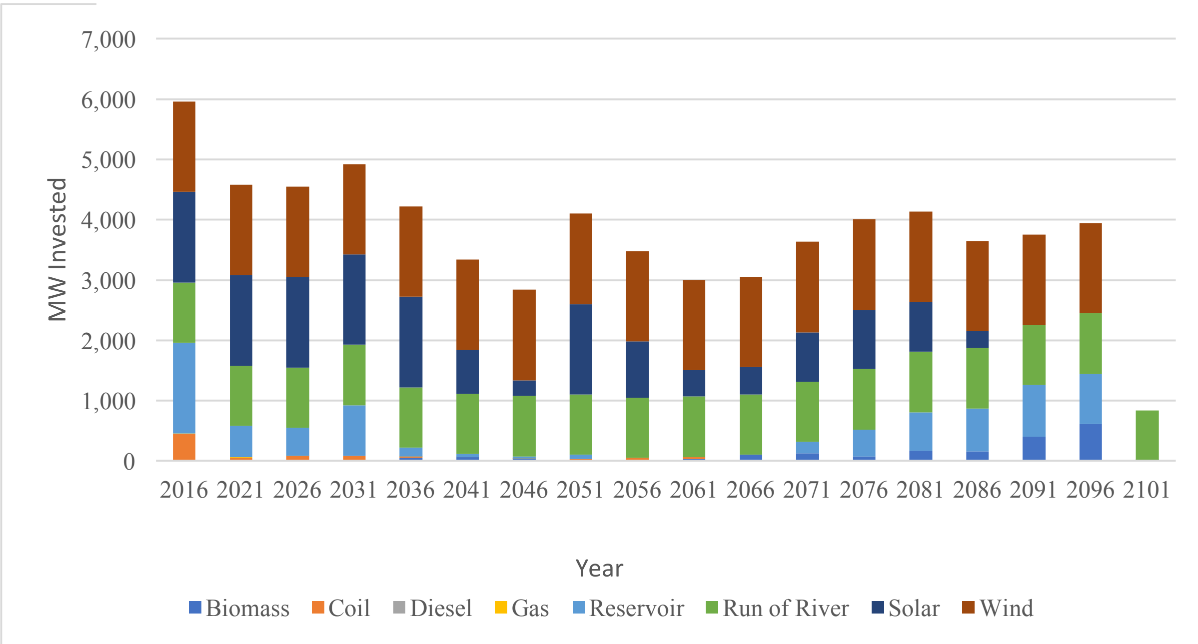


6. Simulation results

The model yields the following results for Case 1, which assumes that climate change affects wind speeds and hence wind farm capacity factors. Figure 5 displays the optimal capacity expansion determined by the model in every period, under this scenario. There is a strong predominance of wind, solar, and run-of-river investments.

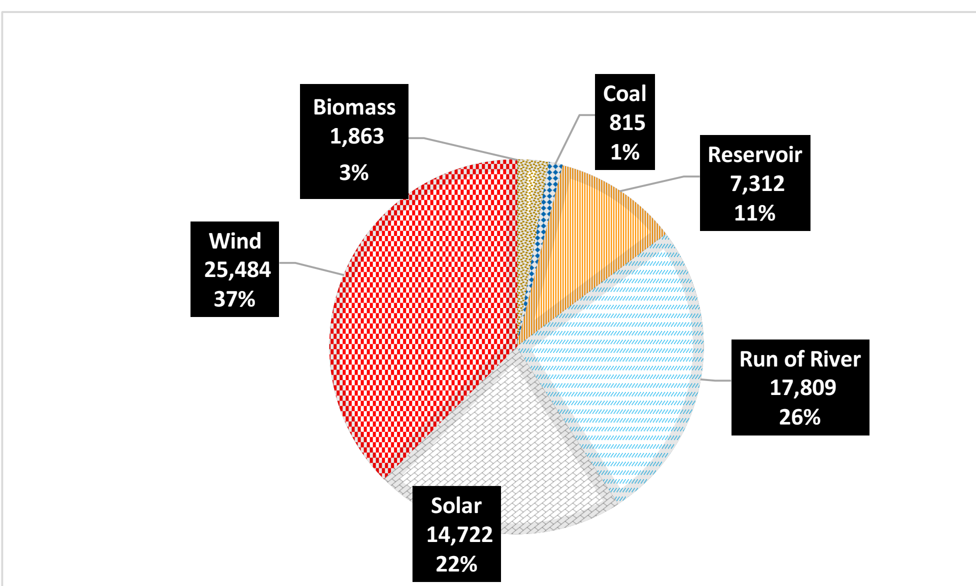
As exhibited in Figure 6, of the total capacity invested throughout the 85-year period, 37% correspond to investments in wind energy (25,483MW), 26% to investment in run-of-river hydro (17,809MW), and 22% to solar energy (14,721MW).

Figure 16: Investments considering impact of Climate Change on wind



As exhibited in Figure 6, of the total capacity invested throughout the 85-year period, 37% correspond to investments in wind energy (25,483MW), 26% to investment in run-of-river hydro (17,809MW), and 22% to solar energy (14,721MW).

Figure 17: Total Capacity investments in 2016-2101, in Case 1



Regarding transmission lines, results show that, in Case 1, it is cost-efficient to invest, during the first period analyzed, in seven lines. The next cost-efficient investment in transmission lines is in year 2046, installing one additional line.

Case 2 assumes that capacity factors remain constant at their 2016 level (i.e., data is not adjusted with projections of effects of climate change on wind speeds). Figure 7 exhibits optimal capacity expansion for every period. Total capacity expansion between 2016 and 2101 are shown in Figure 8. Again, there is a predominance of investments in wind (41%), run-of-river hydro (28%), and solar energy generation (18%). Comparing these outcomes with the previous ones, it is noteworthy that total capacity expansion is lower by 5,750MW when we assume constant wind capacity factors. Although the proportion of investments in wind (with respect to total investments in all generation technologies) increases to 41% (vs. 37% in the previous scenario), the capacity invested in wind is very similar in both scenarios (25,360MW vs. 25,483MW).

Figure 18: Investments considering constant capacity factors on wind, Case 2.

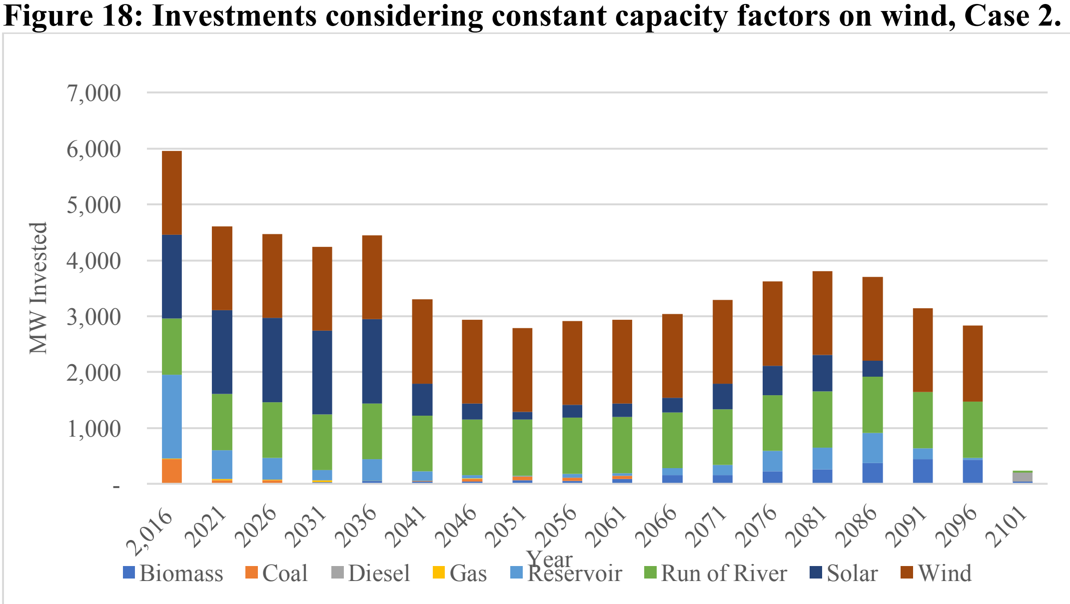


Figure 19: Total capacity investments in 2016-2101, in Case 2

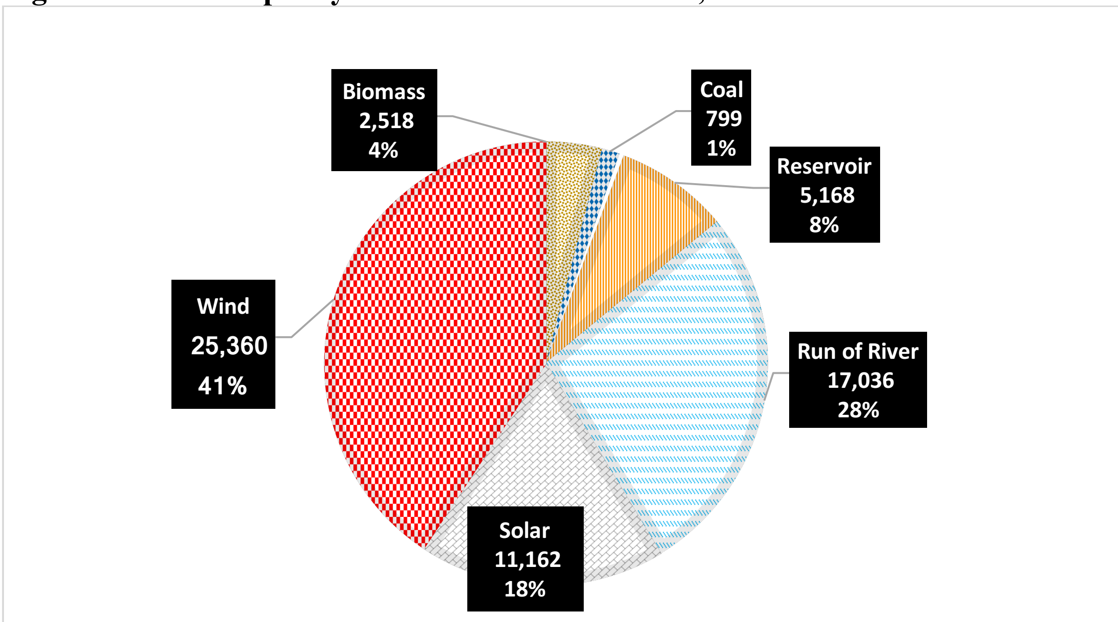


Table 1 compares both cases. It is interesting to note that changes in wind speeds affect not only investments in wind power capacity, but also investments in other power generation technologies. In Case 2, results suggest larger investments in biomass, gas and diesel; and lower investments in hydro and solar power, than Case 1. When influence of climate change on wind speed is taken into account (Case 1), results suggest investing 836MW (16% of the energy matrix) in coal, gas and diesel (taken together); while capacity expansion in coal, gas and diesel amounts to 1.030MW (17% of the energy matrix) in Case 2. The sum of investments between 2016 and 2101 in wind power generation, run-of-river hydro and solar plants is 58,015MW in Case 1, and 53.558MW in Case 2. However, only 123MW correspond to lower investment in wind plants; the large difference between Case 1 and Case 2 is due to the investments in solar energy and run-of-river hydro.

When comparing both cases regarding run-of-river and wind investments, the reader must bear in mind that investment limits were imposed on both types of technologies. Therefore, unconstrained optimization results might have been different. Due to the magnitude of the problem, we optimized the model with 0.01% optimality gap. Hence, relatively small differences between both cases -like those that appear in Table 1 for coal, run-of-river, and wind power- may be partly explained by the optimality gap chosen.

Table 4: Investments by type of technology from 2016-2101 (in MW)

	Case 1 Considering impact of climate change on wind	Case 2 Considering constant wind capacity factors	Difference between investments (MW)
Biomass	1,863	2,518	(656)
Coal	815	799	15
Diesel	4	151	(148)
Gas	17	80	(63)
Reservoir	7,312	5,168	2,144
Run of River	17,809	17,036	774
Solar	14,722	11,162	3,559
Wind	25,484	25,360	124
TOTAL	**68,025**	**62,275**	**5,750**

7. Sensitivity Analyses

7.1. Relaxing the investment limit assumption

The performed studies assumed investment limits for each one of the generation technologies, for every 5-year period. The limit imposed on solar technologies was not binding in either of the studies performed. Results for investment in hydro are close to the limits, and could be different if the investment limit assumption were less restrictive. For run-of-river hydro, we had assumed a 5-year period investment limit of 1,000 MW, and for reservoir hydro the imposed restriction was 1,500 MW, in the whole country. In this section, we relax the investment limits for hydro technologies, to measure how model results would change. We are specifically interested in learning how investment in wind technologies would be affected, when increasing the investment limit for each type of hydro technology by 500 MW.

In Case 1, which takes into account the impact of climate change on wind, results of the sensitivity analysis suggest that 40% of investment is assigned to run-of-river hydro (25,505MW); 34% to wind power plants (21,663MW); and 14% to solar plants

(8,972MW). Figure 9 shows the total investments made from 2016 to 2101, in the various types of generation technologies, when investment limits in hydro are expanded by 500MW per period.

In Case 2, which assumes no effect of climate change on wind speeds, increasing investment limits for hydro yields model outcomes that suggest investing to the limit, both in wind and in run-of-river technologies, in every period up to 2071; henceforth, investment in wind decreases, but investment in run-of-river hydro continues to be constrained at the maximum level. Throughout the 85 years of the study, 40% of investments are assigned to run-of-river hydro, 38% to wind, 13% to solar, 4% to biomass, 4% to reservoir hydro, and 1% to coal. In Case 2, total investments are 1,800MW less than in Case 1. Table 2 summarizes the results of the sensitivity analyses, showing that if the impact of climate change on wind is taken into account, investments in hydro and solar technologies are larger (in MW) than if wind capacity factors are considered constant. In this particular sensitivity analysis, the biggest differences between Case 1 and Case 2 occur in reservoir and in wind investments: Wind investments decrease by 8% if wind capacity factors are affected by climate change; reservoir investments increase strongly (46%). An explanation for this is that, since in Case 1 there are variable capacity factors among hours, months and years, it might occur that wind speeds in some block times or in some places are not enough to produce expected energy. This makes wind investments less attractive than if capacity factors are constant. Therefore, in a situation of less constraint investments in hydro, a higher variability in wind (Case 1) will result in lower investments in wind and higher investments in run-of-river hydro.

Figure 20: Total capacity investments in 2016-2101, in Case 1

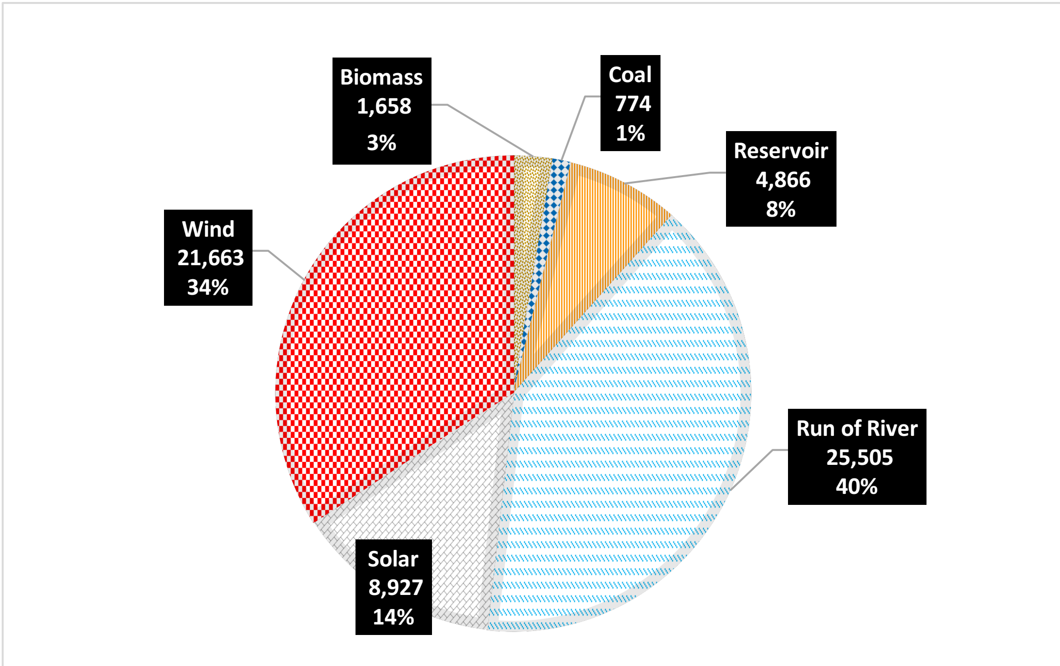


Table 5: Investments (capacity expansions) if investment limit for hydro is expanded by 500MW

	Case 1 Considering impact of climate change on wind	Case 2 Considering constant wind capacity factors	Difference in investments (MW) (Case 1 – Case 2)
Biomass	1,658	2,322	(664)
Coal	774	690	84
Diesel	4	151	(147)
Gas	37	83	(46)
Reservoir	4,866	2,640	2,226
Run of River	25,505	24,755	749
Solar	8,927	7,603	1,325
Wind	21,663	23,390	(1,727)
TOTAL	**63,433**	**61,324**	**1,799**

7.2. Increasing the discount rate to 6%

The discount rate assumed before was 2.715%. We now analyze what would happen with the investments if the project discount rate were 6%, the rate that has been used to discount several energy (social) projects for Chile (Corfo, Oct. 2013; NRDC and ACERA, 2013). Again, we run the model for Case 1 (changing wind capacity factors) and Case 2 (constant wind capacity factors).

Figure 10 exhibits results for Case 1. The larger discount rate naturally causes some investments to be postponed, but the sum of investments by 2101 - in terms of MW per technology- is similar to that using the original discount rate. In the first period (2016), investments are high, to satisfy increasing demand and to reduce costs of the initial energy matrix (which has considerable high-marginal-cost coal, diesel, and gas power plants). Subsequently the model suggests gradually decreasing the amount invested until 2051, and increasing investments thereafter.

Figure 21: Investments considering a discount rate of 6%, in Case 1

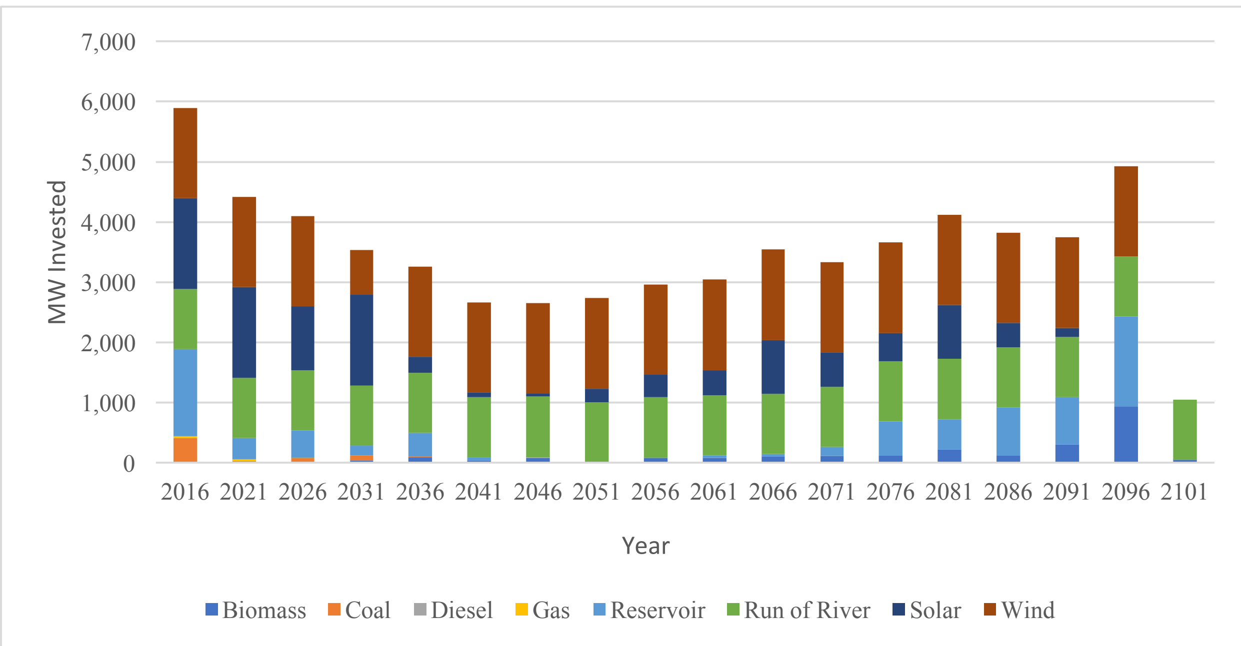


Figure 11 shows that, summing up all the capacity invested in all the periods, results are: 24,733MW invested in wind power (39%), 18,998MW in run-of-river hydro (28%), and

10,371MW in solar energy (16%).

In Case 2 (constant wind capacity factors), increasing the discount rate to 6% results in a decrease in total investments of 4,760MW, in comparison to Case 1. In this case, 42% of total investments are in wind, 30% in run-of-river hydro, 14% in solar, 8% in reservoir hydro, 5% in biomass, and 1% in coal. Table 3 compares both cases for a 6% discount rate. Similarly to previous comparisons, if wind capacity factors are constant, investments are lower in hydro, coal and solar, and higher in biomass, diesel, and gas. Using a 6% discount rate results in higher investments in biomass and gas, and lower investments in coal, diesel, solar, and wind power, than using a discount rate of 2.715%. Similar amounts are invested in hydro power plants with both discount rates.

Figure 22: Total capacity investments in 2016-2101, in Case 1

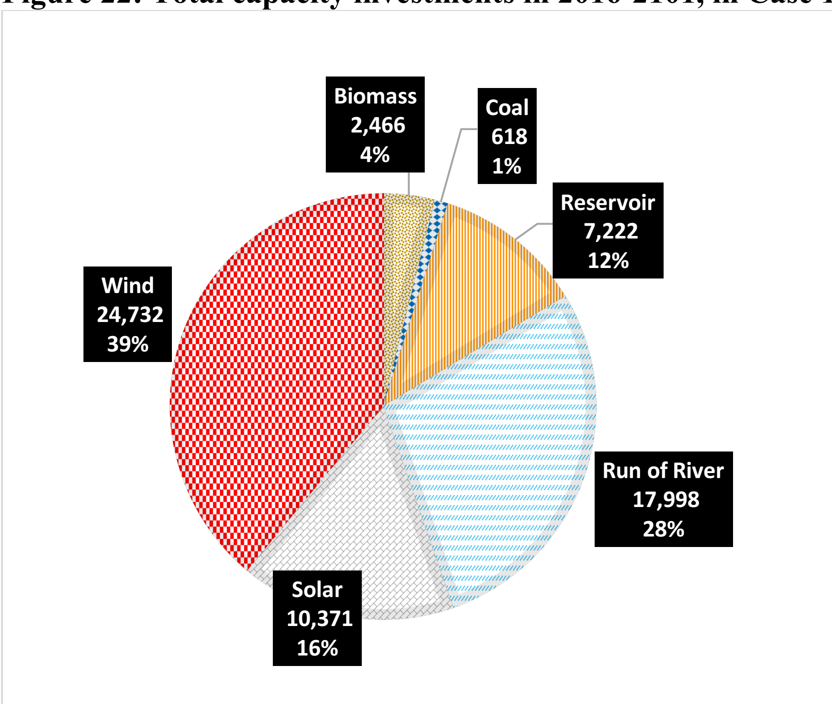


Table 6: Investments (capacity expansions) in the case of considering a discount rate of 6%

	Case 1 Considering impact of climate change on wind	Case 2 Considering constant wind capacity factors	Difference in investments (in MW) (Case 1 – Case 2)
Biomass	2,465	2,941	(476)
Coal	617	588	18
Diesel	2	59	(56)
Gas	58	123	(64)
Reservoir	7,222	4,503	2,718
Run of River	17,998	17,328	669
Solar	10,371	8,408	1,963
Wind	24,732	24,746	(14)
TOTAL	**63,469**	**58,711**	**4,758**

8. Discussion and Conclusions

After concluding that, in Chile, there are no significant correlations between the hourly power generation by wind plants and by other RES technologies, we studied wind speed projections (from the National Center for Atmospheric Research database) under three scenarios of concentration of greenhouse gases, concluding that –due to climate change- wind speeds in Chile will, on average, become slightly more intense, but will also have greater variability. In some nodes in the northern and southern parts of Chile, wind speeds are likely to increase significantly, making wind energy generation more cost-effective. These facts motivated the analysis of the optimal investments for the Chilean energy matrix (2016-2101) in the case climate change affects wind speeds (Case 1), and then comparing those results with the optimal investments in the case wind capacity factors remain unaltered (Case 2).

To do so, we formulated and implemented an optimization model that co-optimizes transmission and generation capacity expansion among power technologies, nodes and years in order to minimize total system costs, while satisfying the increasing demand and fulfilling the national regulations regarding the percentage of generation that must come from RES.

The findings are significant: if climate change affects wind capacity factors, the sum of energy plant investments between 2016 and 2101 are 5.750MW higher than if wind capacity factors remain constant. Investments in biomass, diesel, and gas are relatively lower, and investments in coal, hydro, and solar power relatively higher in Case 1 than in Case 2.

The proportion of investments in wind, respect to total investments in all generation technologies, is lower if climate change affects wind speeds than if it does not (37% versus 41%); however, the capacity invested in wind is very similar in both scenarios (25,484MW vs. 25,360MW). This occurs because in both cases, total optimal investments for wind amount to the maximum allowed in the simulation (1,500MW per 5-year-period, in the whole country). Hence, even when assuming constant wind capacity factors, wind appears as a cost-effective generation technology.

The sum of wind power generation, run-of-river hydro and solar plants is 58,015MW in Case 1, versus 53.558MW otherwise. The largest difference between Case 1 and Case 2 is in investments in solar energy (+3.559MW) and reservoir hydro (+2.144MW). Only 124MW of the difference corresponds to more investments in wind power capacity.

The fact that optimal investments in hydro and solar technologies are larger in a scenario in which climate change produces impacts on wind capacity factors than in a constant wind scenario, could be explained because a greater variability in wind energy generation means that there might be some hours in some years where wind generation falls short from what was expected; therefore, intertemporal optimization requires higher investments in other technologies to be able to satisfy demand. Since wind, hydro, and solar power plants are low-marginal-cost technologies, risks of wind energy shortages are compensated with higher investments in the other RES.

Results are robust to higher investment limits and higher discount rates. The largest differences occur between Case 1 and Case 2 in reservoir and in wind investments, when we increase investment limits for hydro by 500MW (wind investments are 8% higher, and reservoir investments are 46% lower, if wind capacity factors are held constant than if they change).

This study provides optimal power investment projections, showing the increasing importance that RES will have in Chile in the next 85 years, particularly considering the effect of climate change on wind speeds. The share of wind in the Chilean energy matrix will augment, reaching 31% in year 2101. Overall, the Chilean matrix will become more environmentally friendly.

9. References

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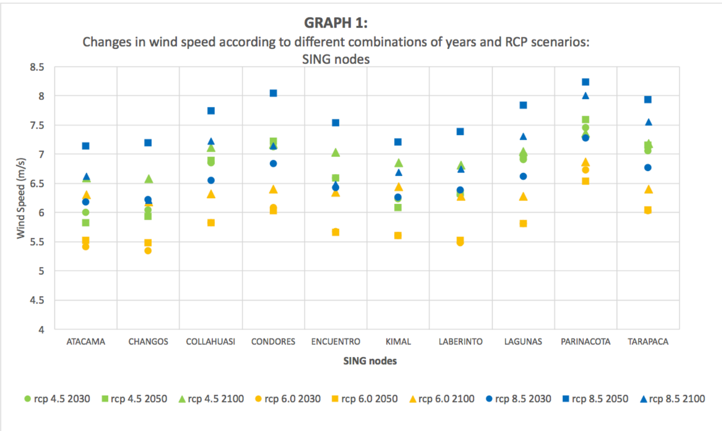
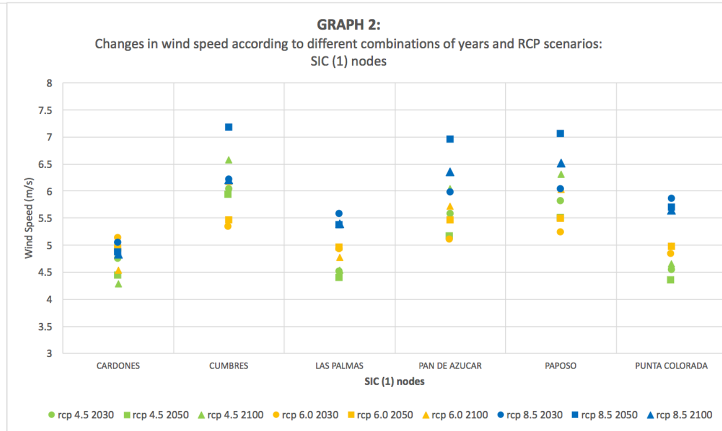
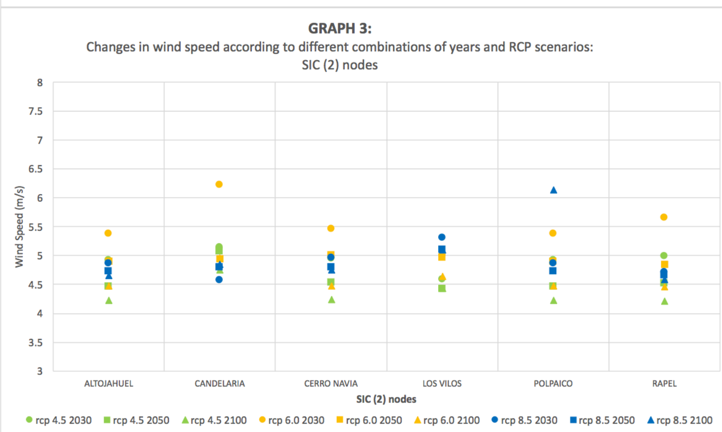
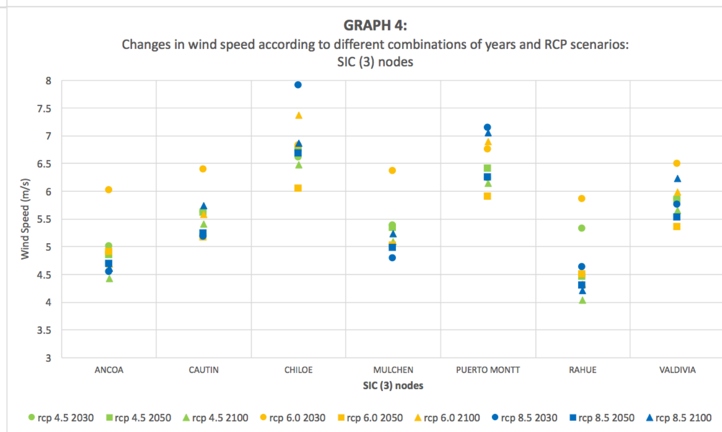
APPENDICES

Appendix 2: Changes in wind speed according to different combinations of years and RCP



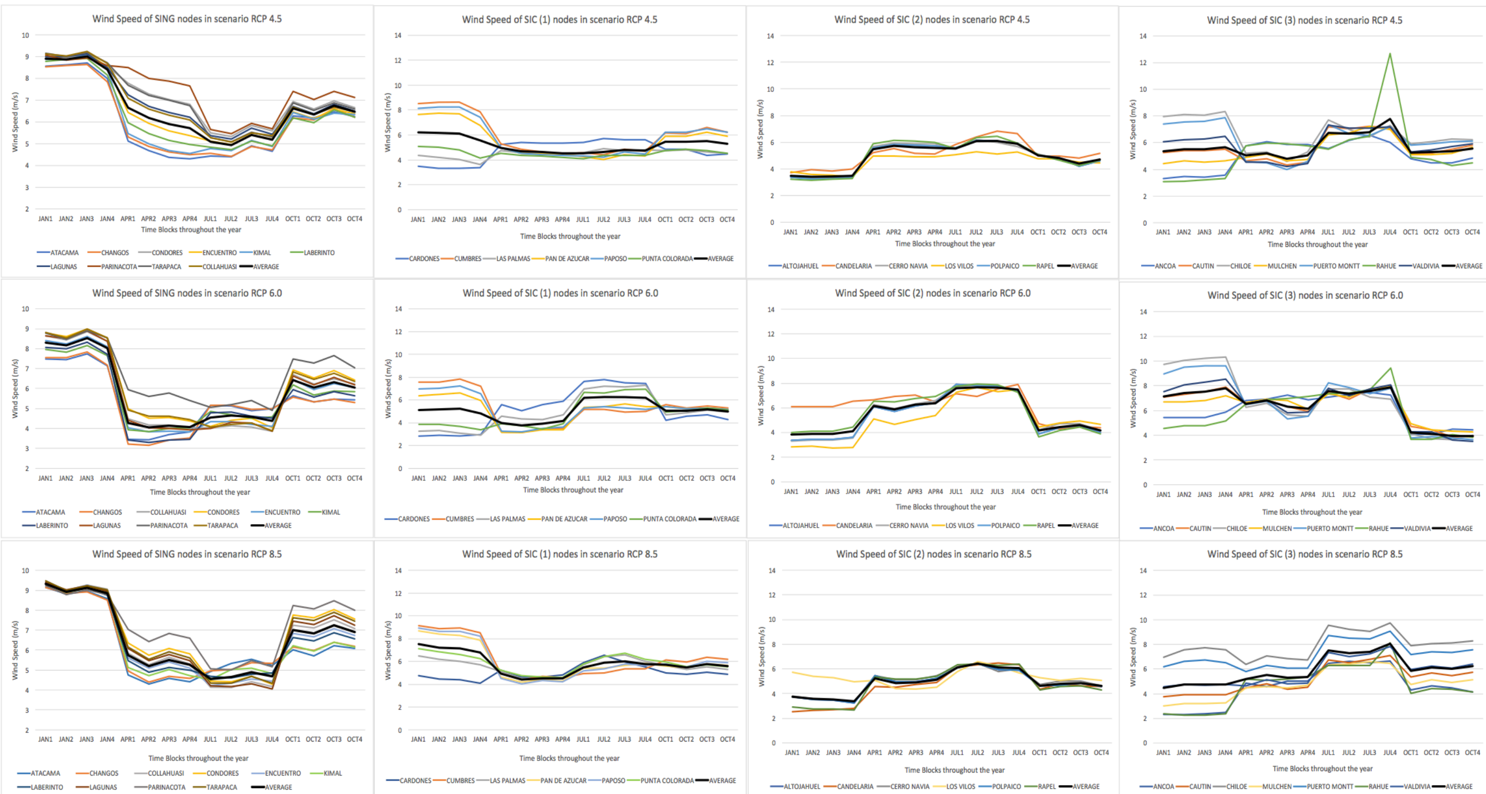






Appendix 3: Wind Speed in different RCP scenarios

COLUMN 1	COLUMN 2	COLUMN 3	COLUMN 4



Appendix 4: Wind Speed in different years and places

COLUMN 1 | **COLUMN 2** | **COLUMN 3** | **COLUMN 4**