UNIVERSITAT POLITÈCNICA DE VALÈNCIA

Escuela Técnica Superior de Ingeniería Industrial

Impact analysis and review of climate drivers to variable renewable energy generation in the Australian National Electricity Market

Trabajo Fin de Máster

Máster Universitario en Ingeniería Industrial-Màster Universitari en Enginyeria Industrial

AUTOR: Alcázar ortega, Manuel

Tutores: Bruce, Anna; Gilmore, Joel; Munro, Jack; Nolan, Tahlia

CURSO ACADÉMICO: 2023/2024

MASTER'S THESIS

Impact Analysis and Review of Climate Drivers to Variable Renewable Energy Generation in the Australian National Electricity Market

Tomás Reilly Rockett

Academic Supervisors:

Anna Bruce, Professor at University of New South Wales

Manuel Alcázar Ortega, Professor at Universitat Politècnica de València

Industry Supervisors:

Joel Gilmore, Iberdrola Australia & Griffith University

Jack Munro, Iberdrola Australia

Tahlia Nolan, Iberdrola Australia

13 December 2023

Abstract

The past decade has seen a rapid uptake of renewable energies around the world, with new technologies becoming more mature and economically feasible. This deployment of renewable energy is not losing momentum and, with the adoption of ambitious net zero policies and greenhouse gas reduction targets, many electricity grids around the world are expected to have a high penetration of variable renewable energies (VREs) in the coming decades. This transition supposes a change in the paradigm of traditional electricity grids, based on dispatchable and predictable energy units. However, VREs require careful planning and management as their intrinsic variability is an added challenge to the reliability and security of the grid. As VREs depend heavily on climate conditions such as wind, cloud cover or temperature, this study has analysed the effect climate drivers cause on VRE generation in the Australian National Electricity Market. An analysis has been made to identify correlations between three climate drivers (El Niño-Southern Oscillation, Indian Ocean Dipole and Southern Annular Mode) and three VRE traces (solar, rooftop PV and wind). Although some trends have been identified, they remain weak and other factors might be much more relevant to the variability in RE generation. However, regional differences have been identified with respect to climate drivers' effect on VREs: southern states such as Victoria and South Australia tend to exhibit lower correlations towards climate drivers than that of eastern states (New South Wales and Queensland)

Resumen

En la última década se ha producido un gran despliegue de energías renovables en todo el mundo, con nuevas tecnologías cada vez más maduras y económicamente viables. Este despliegue de energías renovables no pierde impulso y, con la adopción de ambiciosas políticas de *net zero* y objetivos de reducción de gases de efecto invernadero, se espera que muchas redes eléctricas de todo el mundo tengan una alta penetración de energías renovables intermitentes (VRE) en las próximas décadas. Esta transición supone un cambio en el paradigma de las redes eléctricas tradicionales, basadas en unidades energéticas despachables y predecibles. Sin embargo, las VRE requieren una planificación y gestión cuidadosas, ya que su variabilidad intrínseca supone un reto añadido para la fiabilidad y seguridad de la red. Dado que las VRE dependen en gran medida de condiciones climáticas como el viento, la nubosidad o la temperatura, este estudio ha analizado el efecto que los factores climáticos causan en la generación de VRE en el Mercado Eléctrico Nacional Australiano. Se ha realizado un análisis para identificar correlaciones entre tres impulsores climáticos (El Niño-Oscilación del Sur, Dipolo del Océano Índico y Modo Anular del Sur) y tres recursos de VRE (solar, fotovoltaica de pequeña escala y eólica). Aunque se han identificado algunas tendencias, siguen siendo débiles y otros factores podrían ser mucho más relevantes para la variabilidad en la generación de VREs. Sin embargo, se han detectado diferencias regionales en cuanto al efecto de los factores climáticos sobre las energías renovables: los estados meridionales, como Victoria y Australia Meridional, tienden a mostrar correlaciones más bajas con los factores climáticos respect a los estados del levante (Nueva Gales del Sur y Queensland).

Resum

Durant l’última dècada s'ha produït un gran desplegament d'energies renovables a tot el món, amb noves tecnologies cada vegada més madures i econòmicament viables. Aquest desplegament d'energies renovables no perd impuls i, amb l'adopció d'ambicioses polítiques *net zero* i objectius de reducció de gasos amb efecte d'hivernacle, s'espera que moltes xarxes elèctriques de tot el món tinguen una alta penetració d'energies renovables intermitents (VRE) en les properes dècades. Aquesta transició suposa un canvi en el paradigma de les xarxes elèctriques tradicionals, basades en unitats energètiques despatxables i predictibles. Tot i això, les VRE requereixen una planificació i gestió acurades, ja que la seua variabilitat intrínseca suposa un repte afegit per a la fiabilitat i seguretat de la xarxa. Pel fet que les VRE depenen en gran mesura de condicions climàtiques com el vent, la nuvolositat o la temperatura, aquest estudi ha analitzat l'efecte que els factors climàtics causen en la generació de VRE al Mercat Elèctric Nacional Australià. S'ha realitzat una anàlisi per identificar correlacions entre tres impulsors climàtics (El Niño-Oscil·lació del Sud, el Dipol de l'Oceà Índic i el Mode Anular del Sud) i tres recursos de VRE (solar, fotovoltaica de petita escala i eòlica). Tot i que s'han identificat algunes tendències, continuen sent febles i altres factors podrien ser molt més rellevants per a la variabilitat en la generació de VRE. Tot i això, s'han detectat diferències regionals quant a l'efecte dels factors climàtics sobre les energies renovables: els estats meridionals, com Victòria i Austràlia Meridional, tendeixen a mostrar correlacions més baixes amb els factors climàtics respecte als estats del llevant (Nova Gales del Sud i Queensland).

List of Figures

List of Tables

Contents

List of Abbreviations

NEM	National Electricity Market
VRE	Variable Renewable Energy
ENSO	El Niño – Southern Oscillation
IOD	Indian Ocean Dipole
SAM	Southern Annular Mode
PPA	Power Purchase Agreement
SST	Sea Surface Temperature
GhP	Geopotential height
REZ	Renewable Energy Zone
NSW	New South Wales
QLD	Queensland
VIC	Victoria
SA	South Australia

Introduction

In the present context, climate change is becoming more and more evident and its consequences are increasing both in severity and frequency. Devastating phenomena have been linked to climate change throughout the world and future projections of a business as usual scenario anticipate severe implications both to human society and the world's biodiversity. For this reason, the COP 21 adopted the Paris Agreement. This agreement has a long-term objective of limiting the rise of global mean temperatures to well below 2 °C with respect to pre-industrial levels and, preferably, bellow 1.5 °C which would greatly limit the future effects of climate change.

The objectives outlined in the Paris Agreement translates into a substantial decrease in greenhouse gas (GHG) emissions by 2030, achieving net zero emissions by 2050. In this sense, the International Energy Agency (IEA) set out a road map to achieve net zero by 2050 for the global energy sector [1]. One of the main conclusions of this report is the importance of electrification wherever possible. Following the Net Zero scenario, this will result, in the coming years, in a important increase in electricity demand, as is shown in Figure 1.

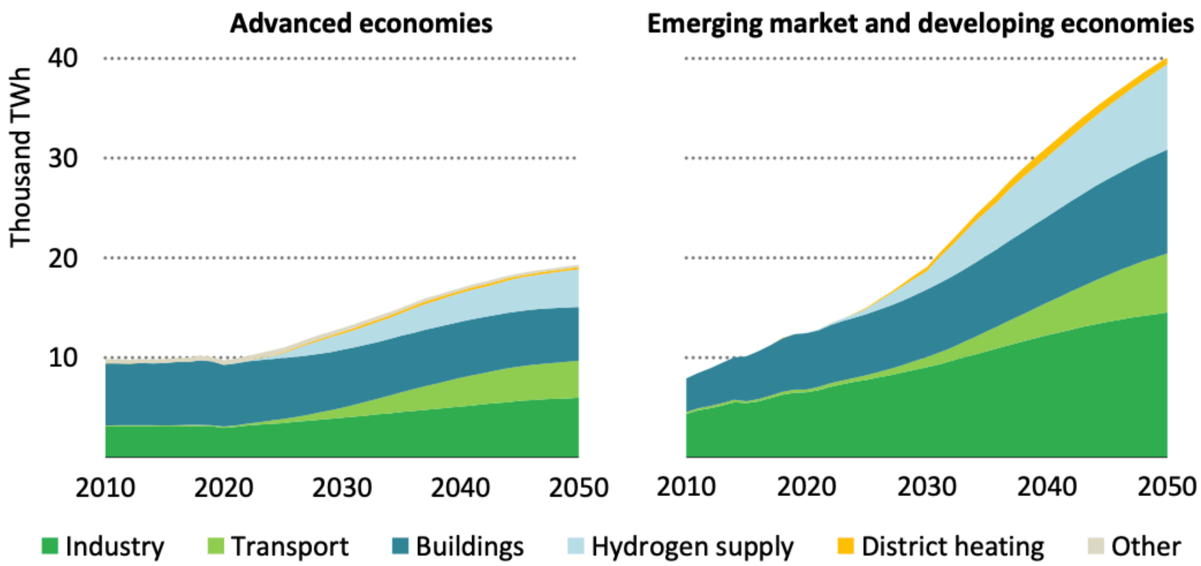


Figure 1 - Electricity demand by sector and regional grouping. Source: [1].

On the other hand, to achieve the Net Zero scenario, this increase in electricity demand cannot be supplied by traditional sources of electricity based on fossil fuels. This is where low emission sources of energy such as renewable energies or nuclear power will play a key role in the decarbonisation of different sectors and industries. From Figure 2, renewable energy generation will triple globally by 2030 and will grow eightfold by 2050, with wind and solar power dominating the energy mix.

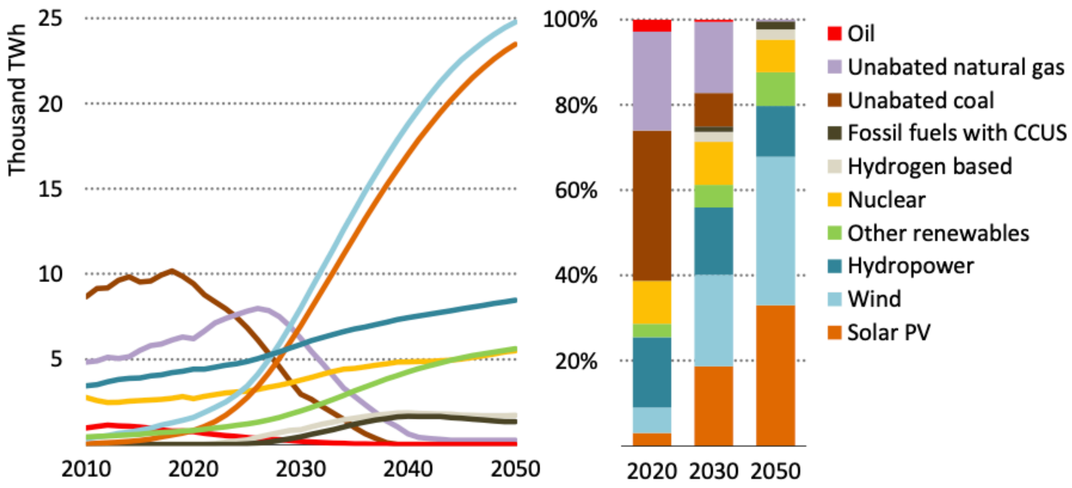


Figure 2 - Global electricity generation by source in the Net Zero scenario. Source: [1].

However, there are certain challenges with integrating a high share of renewable energies into the electrical grid. Variable Renewable Energies (VREs) are clean energy sources that are not dispatchable due to their nature. VREs such as solar and wind energy depend entirely on meteorological conditions and their generation can only be predicted with a certain degree of uncertainty.

This is a major challenge for electricity grids planning on having high penetrations of VREs in the coming decades: following the energy trilemma, the security and reliability of supply has to be guaranteed in order to meet a changing demand. For this reason, planning and forecasting is essential for future grid operators. On the other hand, due to the nature of VREs, there will be certain periods where the electricity generation is below average for a prolonged period of time. This phenomenon is known as renewable energy droughts and it is directly caused by unexpected changes in weather such as lower wind resource or higher cloud coverage.

In this thesis, an analysis will be made to assess the relations between VRE generation and climate drivers in the Australian meteorology. The climate drivers that will be analysed are El Niño-Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD) and the Southern Annular Mode (SAM).

National Electricity Market (NEM)

This study focuses on VRE generation in Australia and the effects climate drivers can have. Therefore, in order to clarify the context around this thesis, a brief introduction to the Australian National Electricity Market is presented.

The NEM, operated by AEMO and regulated by the AER, is one of the worlds longest interconnected power systems stretching a distance of approximately 5000 km [2]. Five regions are present in the NEM: Queensland, New South Wales, South Australia, Victoria and Tasmania. There are 504 registered participants, 10.7 million customers and its total generating capacity is 78,012 MW as of 2023 [3].

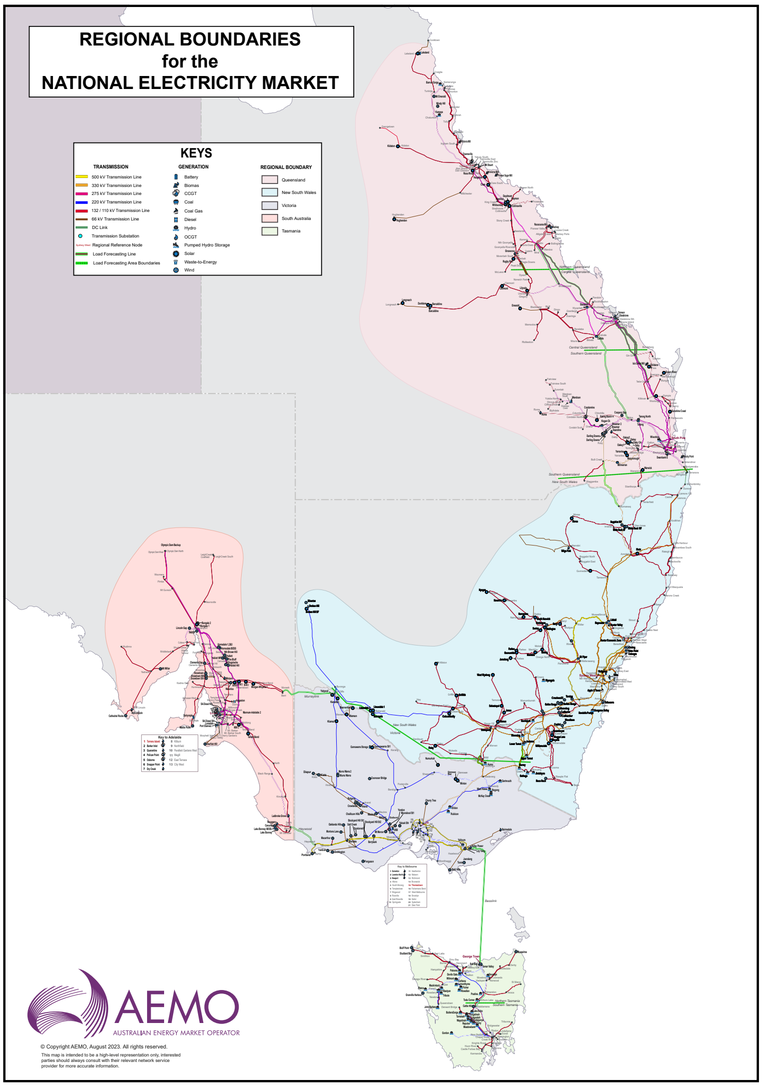


Figure 3 - Visualisation of the NEM network and its five regions. Source: [4]

The generation capacity in the NEM is shown in Figure 4, obtained by AER's State of the energy market 2023 report [3]. As can be seen in Figure 4, black coal is still significant in the NEM's energy mix, although it is being progressively phased out and some plants are even closing down earlier than planned [5]. These phase outs, combined with an increase in electricity demand from electrification, will make the deployment of renewable energies even more important.

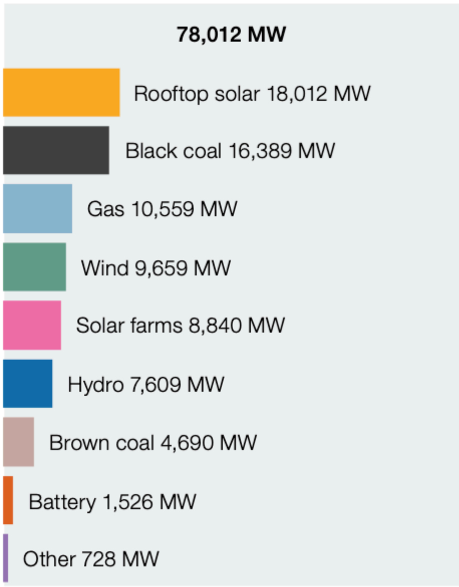


Figure 4 - NEM Generation Capacity by fuel source. Source: [3]

With respect to future projections of the NEM, the 2022 Integrated System Plan (ISP) developed by AEMO [6] considers 4 scenarios: Slow change, Progressive change, Step Change and Hydrogen Supepower. The Step change scenario is considered by most stakeholders to be the most likely scenario. This scenario considers a rapid consumer-led transformation of the energy sector which would achieve the net zero policy goals set out by the Australian government. The forecast capacity of the Step change scenario presented in the 2022 ISP is shown in Figure 5.

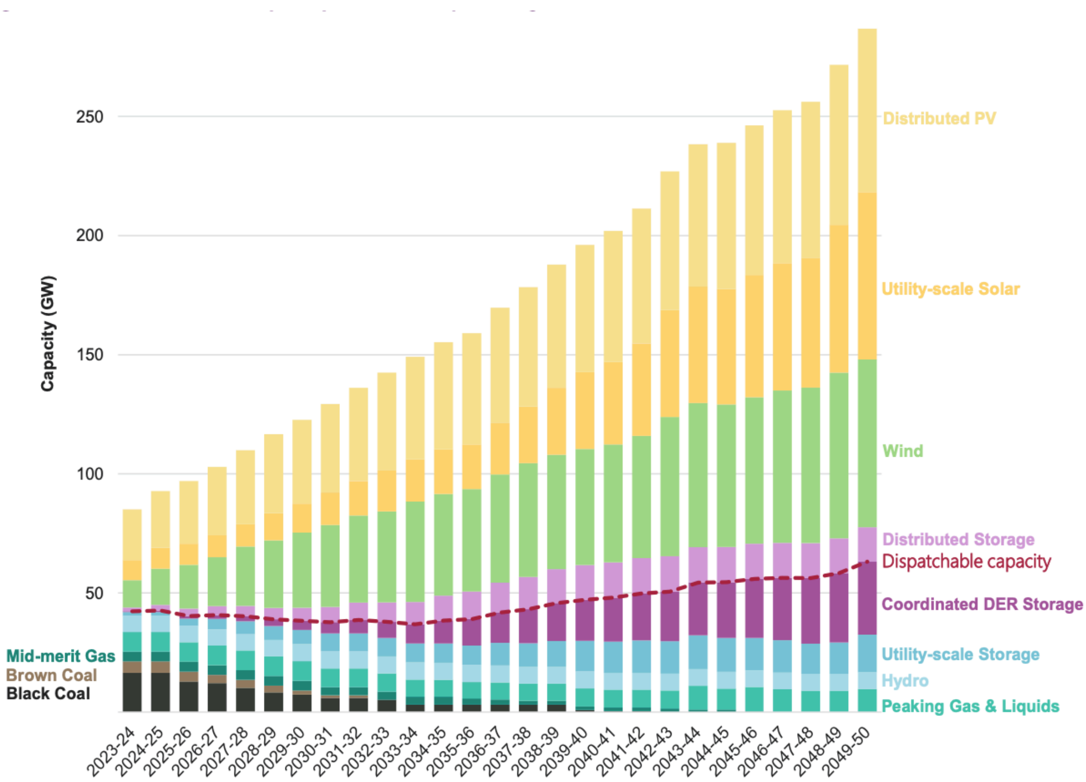


Figure 5 - Forecast NEM capacity for the Step change scenario. Source: [6].

As part of the federal government's plan to reduce 43 % of GHG emissions by 2030 with respect to 2005 levels [7], a renewable electricity target has been set to 82 % by 2030. However, currently the RE share is between 30 and 35 % and important and swift changes are needed in order to reach the target by the end of the decade [8].

In any case, the short and defined timeline set out, together with the ambitious target requires careful planning and extensive studies of the integration of VREs to the australian grid.

Iberdrola Australia

As a key participant of this thesis, this section will present a brief introduction to Iberdrola Australia's background and its main motivations towards this study.

Iberdrola Australia is an energy producer and supplier with a portfolio of wind and solar capacity across New South Wales, Victoria, South Australia and Western Australia. Table 1 shows the RE assets owned and contracted by Iberdrola Australia as of 2023 [9].

Table 1 - Iberdrola Australia's RE assets as of 2023.

Asset	Capacity	Location	Owned/Contrac
Avonline Solar Farm	245 MWp	NSW	Owned
Bodangora Wind Farm	113.2 MW	NSW	Owned
Capital Wind Farm	140.7 MW	NSW	Owned
Flyers Creek Wind Farm	145 MW	NSW	In construction
Lake Bonney Wind Farm	278.5 MW	SA	Owned
Port Augusta RE Park	217 MW wind 110 MW solar	SA	Owned
Walkaway Wind Farm	89.1 MW	WA	Owned
Woodlawn Wind Farm	48.3 MW	NSW	Owned
Cherry Tree Wind Farm	57.6 MW	VIC	PPA
Collector Wind Farm	227 MW	NSW	PPA (60 %)

With more than 95 % of their electricity generation coming from renewable sources, Iberdrola Australia has a big interest in understanding the effects of RE underproduction and the possibilities of having RE droughts. In this sense, the role climate drivers play toward RE production in the NEM will broaden Iberdrola Australia’s knowledge in this area.

This thesis is organised as follows:

In the Chapter 1, a review of the three climate drivers is presented (ENSO, IOD and SAM) with an explanation of each of their causes, the different methods used in the literature to measure them and their effects on the Australian climate. In the second part of this chapter, a state of the art in the study of climate drivers and VRE generation is outlined. Articles focusing on regions other than Australia are presented to study the different methodologies used.

In Chapter 2, the core of this thesis is presented where the analysis into the effects of each climate driver on VRE generation data is made. Firstly, a detailed description of each of the data corresponding to the three climate drivers and the three VRE generation traces (wind, solar and rooftop) is made. Next, the methodology of the analysis is presented and divided into the continuous correlations and discrete correlations. In Section 2.3 and 2.4, the results of the analysis are shown as scatter plots (for continuous analysis) and boxplots (for discrete analysis).

Finally, in Chapter 3 a discussion on the results and its implications is presented. Firstly, a discussion into the results obtained in Chapter 2 is conducted. In this part, a quantification of the results and their implications is detailed. In the second part of this chapter, a discussion into the thesis and its objectives is presented, with a section identifying further steps and gaps that could be continued from this study.

Chapter 1

Literature Review

1.1. Introduction

In this chapter, a review of the climate drivers and their impact to VRE is presented. Firstly, the causes and consequences associated to the climate drivers studied in this thesis is described, with an emphasis on their effects towards the Australian climate. The climate drivers present in this thesis are: Indian Ocean Dipole (IOD), Southern Annular Mode (SAM) and El Niño-Southern Oscillation (ENSO).

In the second part of the chapter, the state of the art of studies analysing the impact of climate drivers to VRE generation is presented. Notably, these studies will be from analysis conducted in other countries, such as the U.S. or Colombia, but the methodologies of the analysis remain relevant to this thesis.

1.2. Climate Drivers

In this section, a detailed description of each of the climate drivers will be presented. As was mentioned above, each climate driver is described, identifying the main causes, its characteristics and the consequences the climate driver produces, especially towards the Australian Climate.

1.2.1. El Niño-Southern Oscillation (ENSO)

The ENSO climate driver combines the El Niño/La Niña oscillation and the Southern Oscillation. The first, relates to the variation in winds and sea surface temperature (SST) in the Pacific Ocean. The latter is the atmospheric component relating to the El Niño/La Niña oscillation. The strong correlation between both of these drivers is the reason for coupling them into a single one.

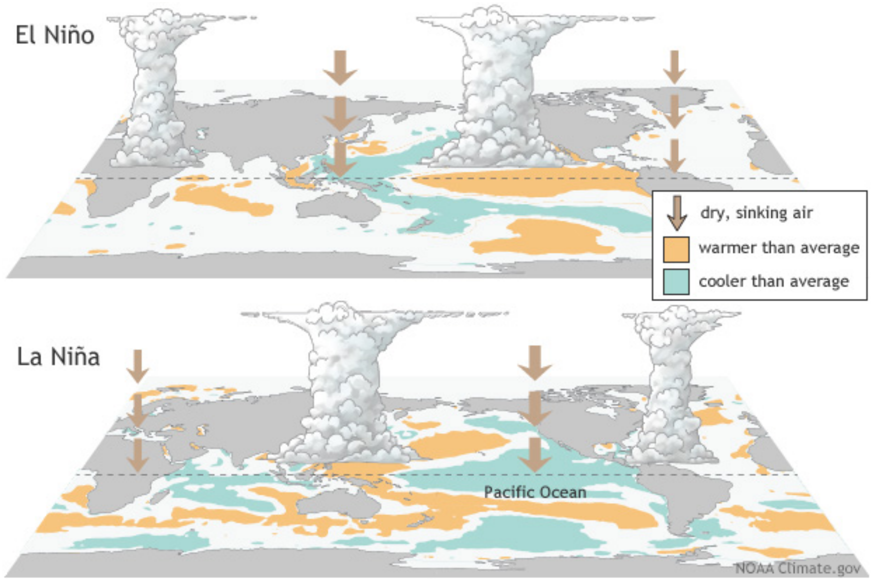


Figure 6 - Main climate effects of ENSO for El Niño and La Niña states. Source: [10]

The El Niño oscillation was firstly identified in the 1600's off the coast of Peru identified as a warmer than usual sea current [11]. However, extensive research into the periodicity and causes of this climate driver didn't occur until the 1980s [12]. This climate driver oscillates between three different phases, occurring every 2-7 years, although El Niño occurs with a higher frequency than La Niña [13]. The three different phases associated to ENSO are:

- El Niño: this period is characterised by warmer than usual SST located in the central-east equatorial Pacific, sustained during a long period of time [14]. It typically lasts 9-12 months although, exceptionally, prolonged El Niño episodes last 2 years and up to 3-4 years [13].

- Neutral: this is a transitory phase where the indicators are too weak to be identified either with El Niño or La Niña periods.

- La Niña: this period is characterised by cooler SST in the central-east equatorial Pacific. It usually lasts between 1 and 3 years [13].

Both La Niña and El Niño tend to develop during March – June and reach peak intensity during December – April and finally weaken in May – July.

Indicators

Depending on the meteorological institute, this climate driver can be measured using different indicators and criteria in order to predict and identify a specific state [12]. However, most methodologies use, among other indicators, the Niño 3.4 which represents the region in the Pacific Ocean surveyed for SST anomalies, as can be seen in Figure 7.

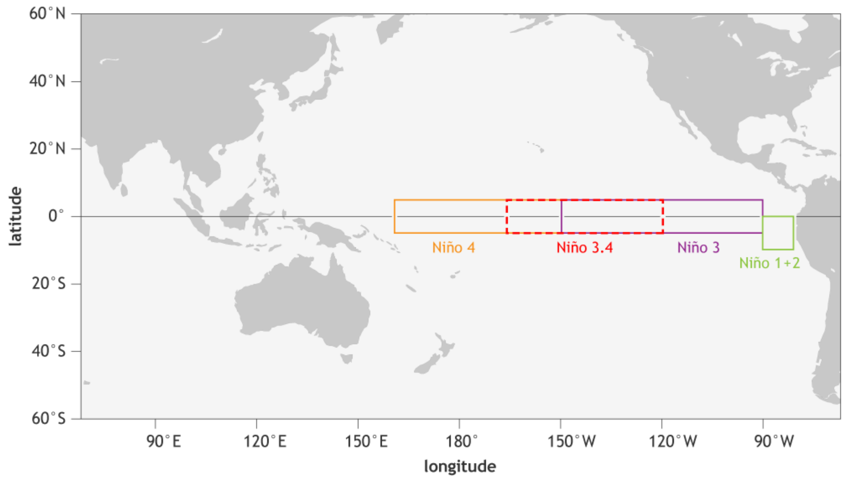


Figure 7 - ENSO regions for SST measurements. Source: [10]

On the other hand, the Southern Oscillation Index (SOI) is the measure related to the difference in sea level pressure between the western and eastern tropical pacific. More specifically, it is the standardised difference of observed sea level temperatures between Tahiti and Darwin, Australia. Negative values of SOI are related to warmer El Niño periods while positive SOI values are associated to La Niña periods with colder SST values.

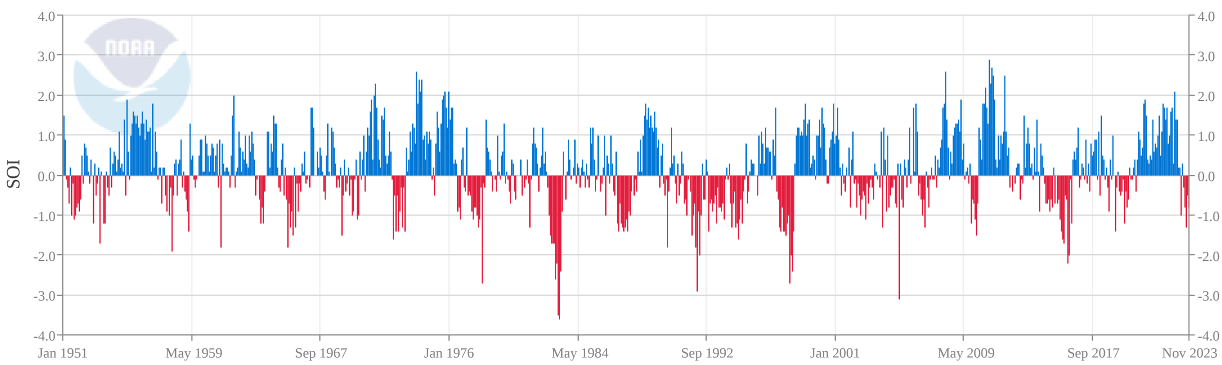


Figure 8 - Southern Oscillation Index (SOI) from 1951 to present. Source: [15]

Finally, another useful indicator is the Multivariate ENSO Index, which groups together several measurements in order to produce one coherent indicator. The original MEI was proposed in 1993 [16] , although a new version of the MEI (MEI.v2) has been developed considering 5 variables: sea level pressure, SST, surface zonal winds, surface meridional winds and Outgoing Longwave Radiation. Many studies use the MEI as a suitable index to analyse the correlation of ENSO with different climate events ([17] [18] [19]). The vauels of the MEI can be seen in Figure 9.

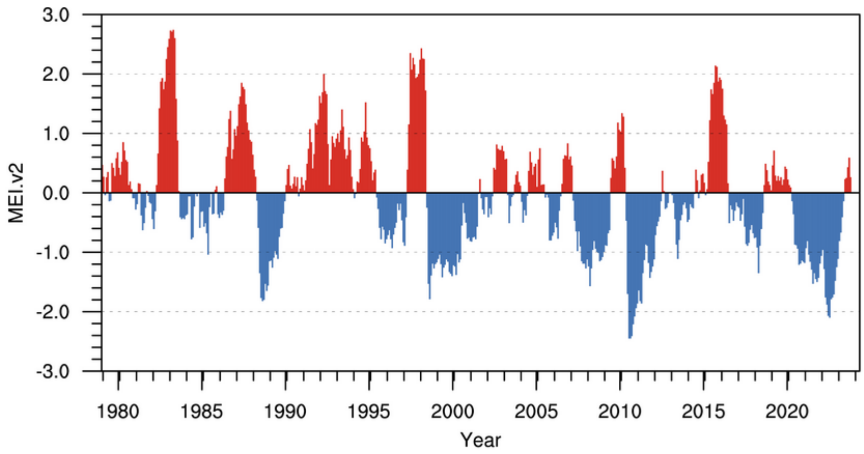


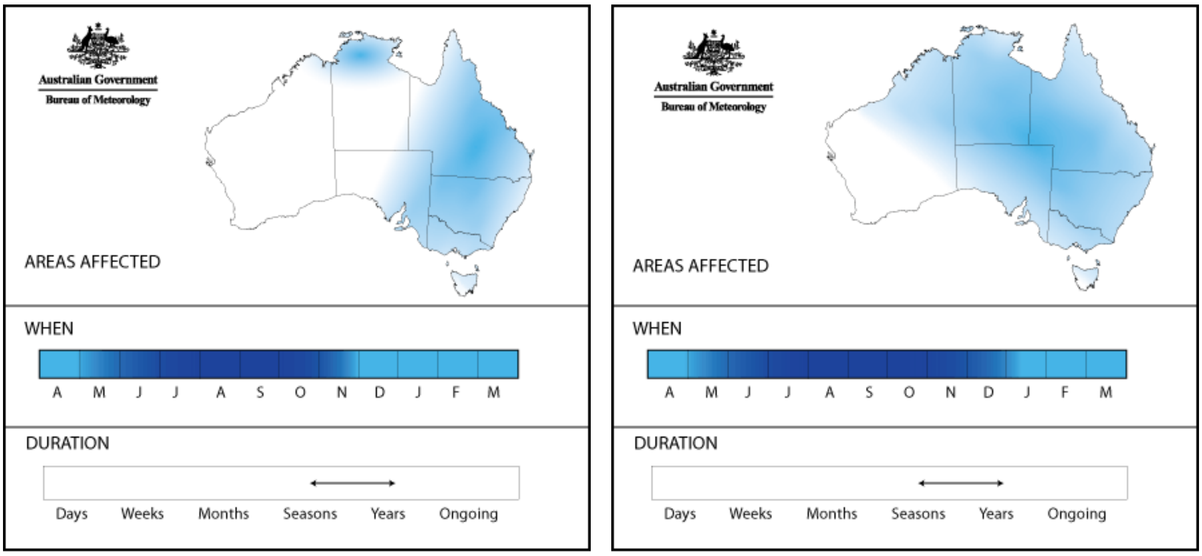
Figure 9 - Multivariate ENSO Index (MEI) Version 2. Source: [20].

In order to identify an El Niño period, the Australian Bureau of Meteorology (BOM) requires any three of the following criteria to be satisfied [21]:

- SST: Temperatures in the Niño 3 or Niño 3.4 regions (Figure 7) are 0.8 °C warmer than average.
- Winds: Trade winds in the western or central equatorial Pacific Ocean have been weaker than average in any three of the four last months.
- SOI: The three-month average SOI is lower or equal to -7.
- Models: most climate models show an anomaly in SST of +0.8C

Effects on the Australian Climate

As can be seen in Figure 6, the ENSO climate driver generally causes a drier and warmer climate in Australia during an El Niño phase, and a cooler and more wet climate during La Niña years. The location and duration of the effects El Niño and La Niña have on Australia can be seen in Figure 10.



(a) El Niño area of effects (b) La Niña area of effects

Figure 10 – Location, timeline and duration of effects for El Niño (a) and La Niña (b) phases. Source: [22]

The effects associated to El Niño, which tends to last approximately a year, is associated with lower than average rainfall in winter and spring over most of eastern Australia: 9 out of the 10 driest winter-spring periods on record for eastern Australia occurred during El Niño phases [23]. Another effect of El Niño is warmer than average temperatures in most of Southern Australia which, together with decreased cloud coverage, further increases the daytime temperatures. Other effects associated to El Niño years, identified in [23], are: reduced tropical cyclone numbers, later monsoon onset, increase fire danger in southeast Australia or decreased alpine snow depths.

The effects associated to La Niña years are mainly an increase in rainfall in eastern Australia, with a decrease in average temperatures and an increase in cloud cover [24]. However, it is important to mention how recent studies have looked at the different behaviour between La Niña periods and how not all La Niña years can have the same effects on climate. According to [25] these variations between periods could be mainly due to the interaction with other climate drivers such as the Indian Ocean Dipole (IOD) or the Madden-Julian Oscillation.

1.2.2. Indian Ocean Dipole (IOD)

The Indian Ocean Dipole (IOD) episodes are determined by the variation with respect to average values of the SST in the tropical western and eastern parts of the Indian Ocean.

Three different states occur in the IOD:

- Positive IOD: these episodes are characterised by cooler than average SST in the tropical eastern Indian Ocean and warmer than average temperatures in the western part. In a positive IOD, westerly winds become weaker along the equator which causes the warmer water to shift towards Africa, and the cooler waters to rise up from the deep oceans near Australia.

- Neutral IOD: in this phase, the DMI values are between -0.4 °C and +0.4 °C, too weak to determine a positive or negative IOD event.

- Negative IOD: these events are characterised by cooler than average SST in the tropical western Indian Ocean and warmer than average temperatures in the eastern part. In this phase, westerly winds intensify along the equator, moving warmer waters closer to Australia.

Indicators

To identify different periods of the IOD, the main index that is used is the Dipole Mode Index (DMI), defined in 1999 by [26] which represents the difference between SST anomalies in two regions of the Indian Ocean: IOD west and IOD east; as can be seen in Figure 11.

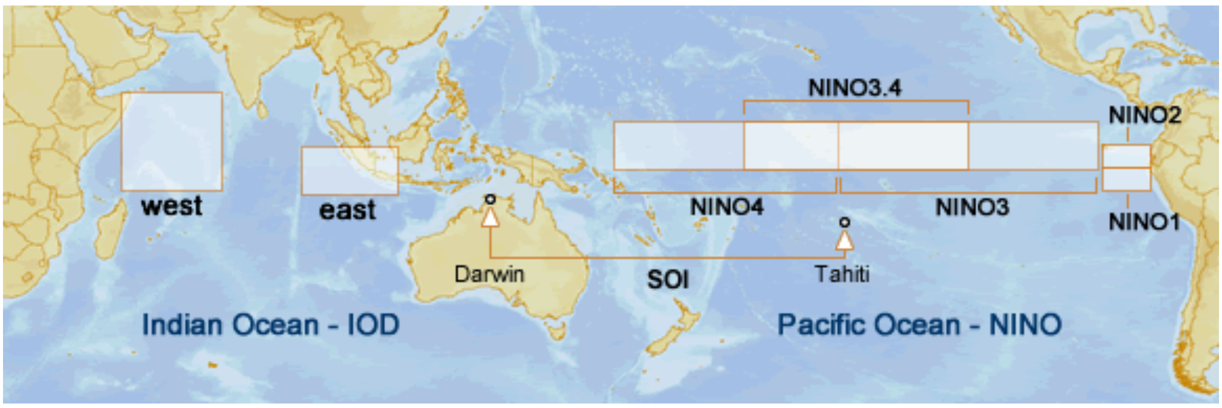


Figure 11 - Regions used to monitor ENSO and IOD events. Source: [27].

The Australian BOM identifies a positive SOI when the DMI presents sustained values greater than 0.4 °C; and a negative SOI event is considered with sustained values of DMI below -0.4 °C [27]. In Figure 12, the historical DMI values are presented since 1950.

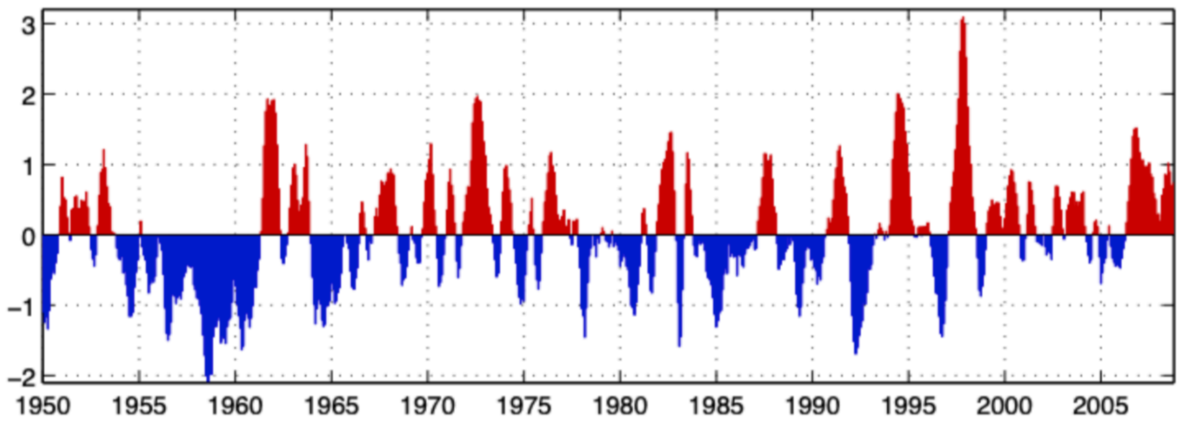


Figure 12 - Historical DMI values (°C) since 1950 to 2010. Source: [28]

Effects on the Australian Climate

As is shown in Figure 13, the average timeframe of IOD events is usually a few months or a season, rarely reaching a year in legth. On the other hand, it usually starts in May, peakd in Auguts and weakens in November. Finally, the main effects of IOD events are experienced across the southern parts of Australia and the northern tip [29], although as will be presented in the following, many other parts of Australia are also affected.

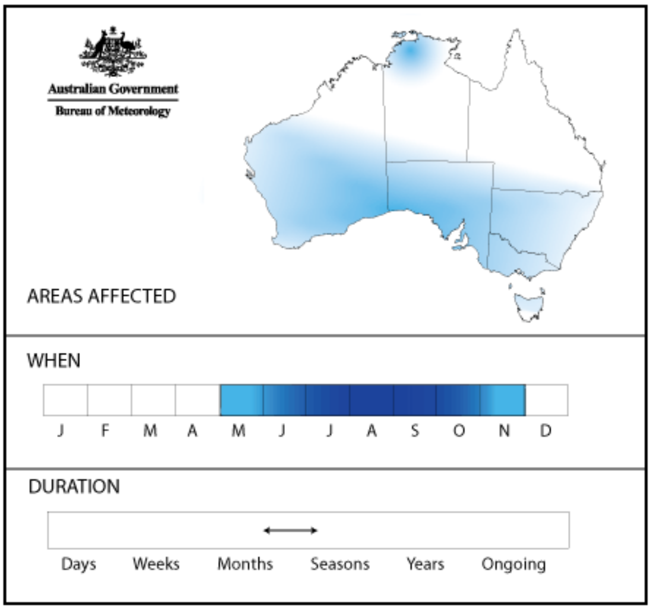
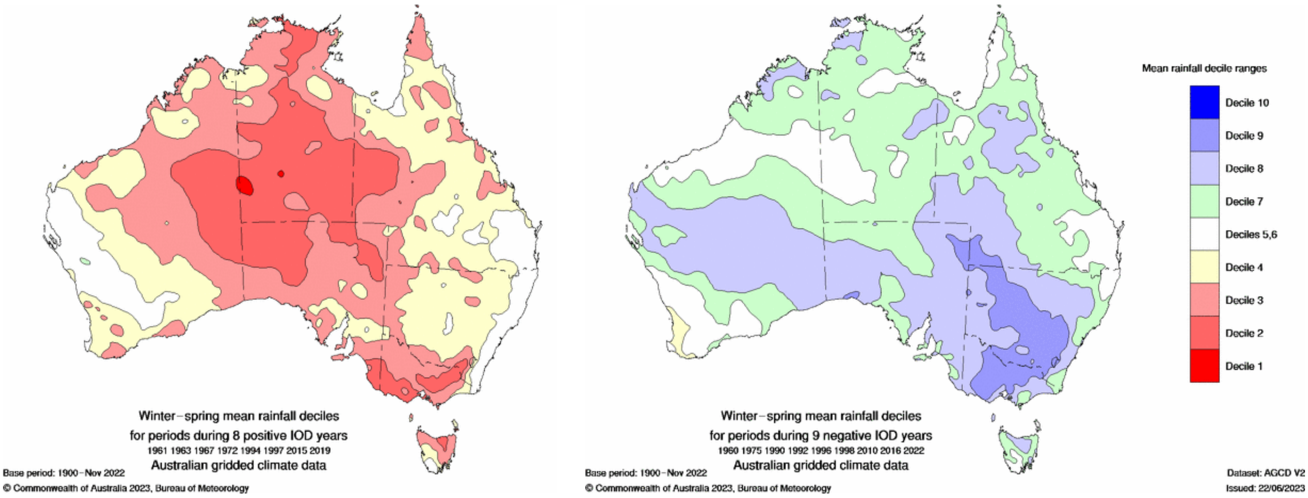


Figure 13 - Location, timeline and duration of effects for IOD. Source: [29].

One of the main effects attributed to the IOD is the variation of rainfall, which, as can be seen in Figure 14, a negative IOD tends to result in more rainfall than average in southeastern Australia while a positive IOD results in less rainfall than averahe across central and southern

Australia. On the other hand, the correlation with temperatures isn't as evident: warmer temperatures than usual in western Australia are associated to positive IOD although there is also a decrease in the minimum temperatures for northern Australia; conversely, for negative IOD events, cooler temperatures in the southeast are usually observed although an increase in mean temperatures is observed in the northen part of the country.



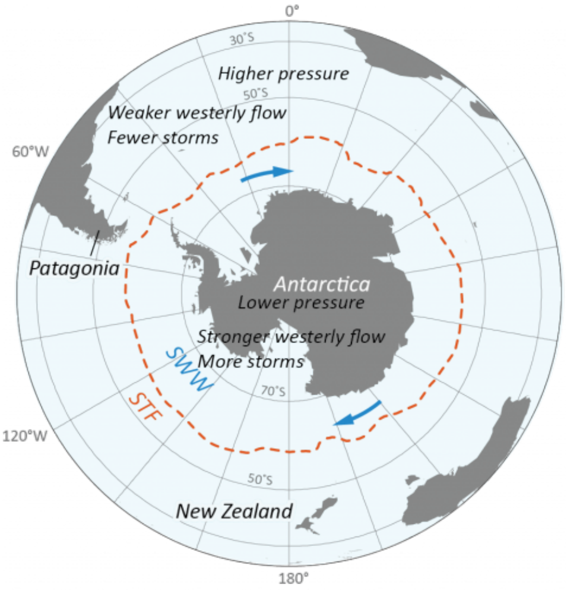
(a) Positive IOD (b) Negative IOD

Figure 14 – Winter-spring mean rainfall for 8 positive IOD years (a) and 9 negative IOD years (b). Source: [29].

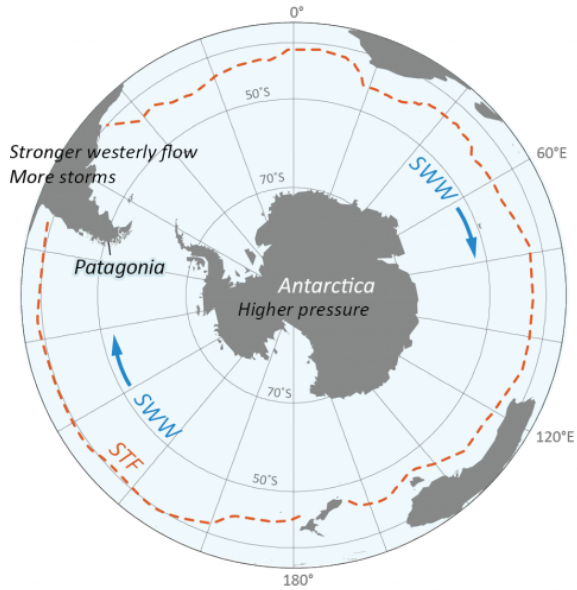
Another important factor is the interaction of the IOD with ENSO: when El Niño coincides with a positive IOD, the effects are increased with even hotter and dryer periods [28]. Similarly, a negative IOD and a La Niña will also increase the above-average rainfall.

1.2.3. Southern Annular Mode (SAM)

The Southern Annular Mode (SAM) is the north/south oscillation of the belt of strong westerly wind belt that circles the Antarctica. It is also known as the Antarctic Oscillation (AAO). As can be seen in, a positive SAM occurs when the westerly winds contract poleward, while a negative SAM is caused by the westerly winds going north [30].



(a) Positive SAM



(b) Negative SAM

Figure 15 – Positive (a) and Negative (b) phases of the Southern Annular Mode (SAM) climate driver. Source: [30].

As mentioned above, the two possible state of the Southern Annular Mode are:

- Positive SAM: this event is identified with a poleward shift of the southern westerly winds. This shift also increases the intensity of the winds with lower pressures located near the Antarctica, increasing the probability of storms in the area.

- Negative SAM: this period is associated with a northern shift of the trade winds, with higher pressures located in the Antarctica area and stronger winds and more frequent storms at higher latitudes.

An increased tendency of positive SAM events during the summer and autumn months (December – May) can be observed in Figure 16. This tendency is believed to be due to ozone depletion and greenhouse gas levels in the atmosphere [30] [31]. According to [32], the increase in CO_2 levels leads to a poleward shift and an increase in intensity of the southern westerly winds.

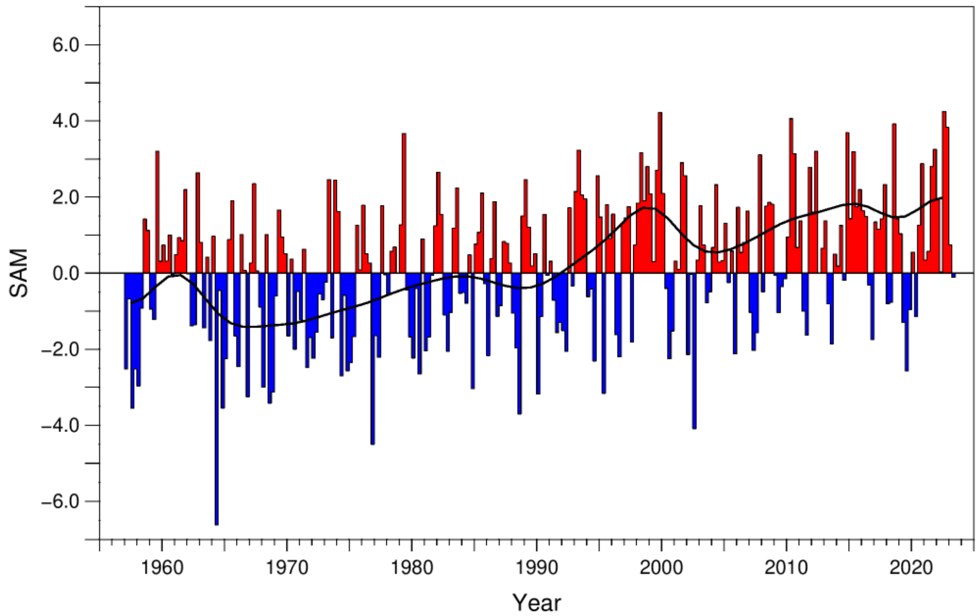


Figure 16 - Seasonal values of the Marshall SAM index, updated from [33]. The black line represents decadal variations. Source: [34]

Indicators

There exist many different methodologies to obtain a SAM index [35] depending on the time period (start and end years), the different sea level pressures (700 or 850 hPA GpH), the time scale (monthly or seasonal) or the source of raw data (station readings or gridded data). However, two main methods are used for the determination of most of the SAM indices:

- Principal Component (PC) analysis: where the firs PC of the southern hemisphere climate variables are assessed, such as geopotential height, mean sea level pressure, temperature, etc.

- Gong and Wang (1999) method: where the difference of normalised zonal mean pressures between 40° S and 65° S is calculated for every month.

In this study, the Marshall SAM index will be used [31] [34], which uses the Gong and Wang definition. This index is based data from six different stations measuring the monthly mean difference of the mean sea level pressure. From this data the SAM index is obtained, as shown in Figure 17, spanning from 1957 to present with a monthly resolution.

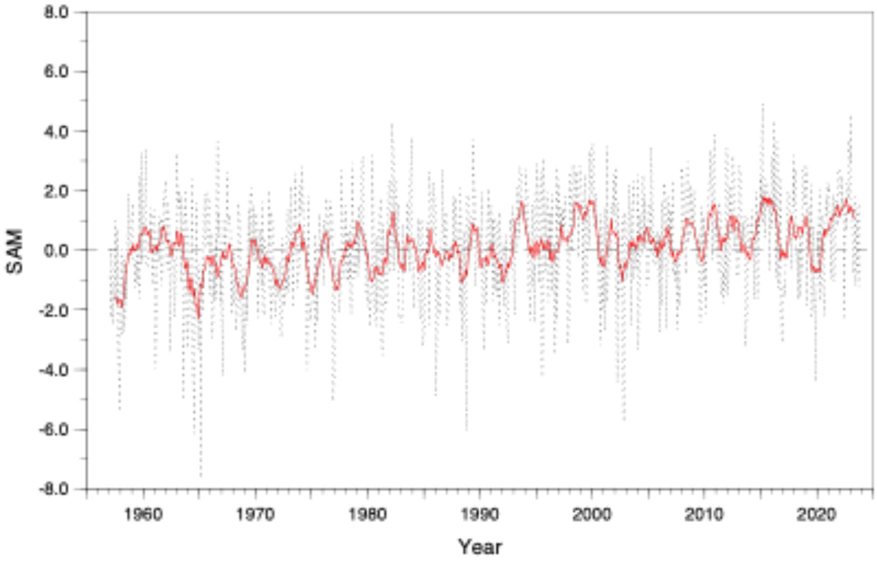


Figure 17 – Monthly Marshall SAM index (black dotted line). The red line represents the 12-month running mean. Source: [34].

Effects on the Australian Climate

SAM is one of the predominant climate drivers of Australian weather, especially relating to rainfall. However, the contribution of SAM towards climate variability in Australia has just recently started to be studied and it is still a very active area of research.

As can be seen in Figure 18, its effects are widespread across the southern parts of Australia, and there are no specific months or seasons when it is more predominant. On the other hand, its frequency can vary in a weekly or monthly time scale. The main effects positive and negative SAM events have on the Australian climate are the increase or decrease of average rainfall, mainly due to the trade winds becoming drier when crossing Australia from west to east (during positive SAM periods), or allowing for more humid winds to enter the eastern coast when the trade winds are at lower latitudes (negative SAM events).

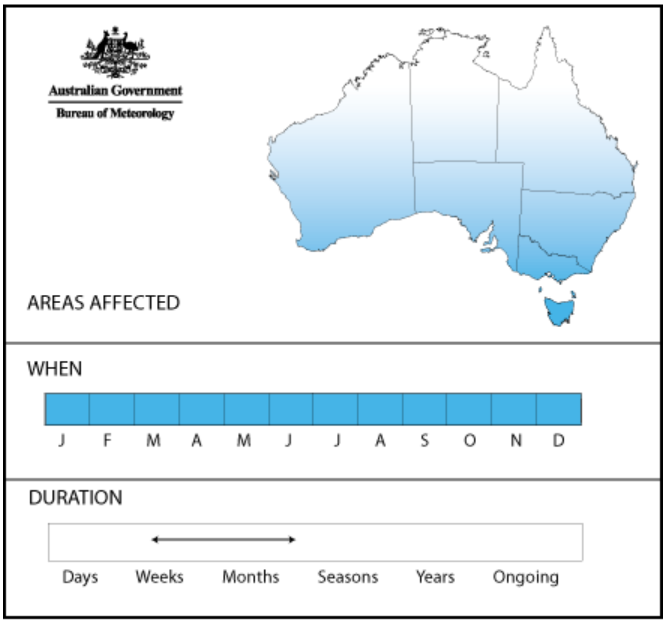


Figure 18 - Location, timeline and duration of effects for IOD. Source: [36].

Depending on the season in which a positive/negative SAM occurs, different correlations are identified relating to the Australian weather:

- Positive SAM - Summer: there is an increased chance of summer rain in south-eastern Australia.
- Negative SAM - Summer: there is a decreased chance of summer rain in south-eastern Australia.
- Positive SAM - Winter: there is an increased chance of rain in eastern Australia, and a decreased chance of rain in the southern regions.
- Negative SAM - Winter: there is a decreased chance of rain in the eastern regions, and an increase chance of rain in southern and western parts of Australia.

Finally, as was the case with ENSO-IOD interactions, there also exists a correlation between ENSO events and positive or negative SAM periods: positive SAM events tend to occur more frequently during La Niña periods, while a negative SAM is more frequent during El Niño events [36].

1.3. Impact of Climate Drivers to Variable Renewable Energy (VRE)

In this section, a review of existing studies relating to VRE generation and climate drivers will be assessed. The impact of climate drivers towards VRE generation is becoming a very active research topic although, due to the local nature of these studies, there are few articles specifically relating to the impact of climate drivers towards Australian VRE generation.

The main articles studied have assessed this impact in other locations such as South America or Asia with conclusions that cannot be inferred towards an Australian scenario. However, their methodologies and the data that has been used remains relevant toward this thesis.

Due to the widespread effects of ENSO, detailed in Section 1.2.1, and the extensive research of this climate driver, most studies focus on the correlation of VRE generation to ENSO in different locations ([37] [38] [39] [40] [41]). Due to the nature of this climate driver, most of these studies have analysed the effects for South America or the U.S. However, a very recent and relevant study focused on Australia has been published (Richardson et al., 2023) [38]. These studies can be classified into two groups:

(i) studies analysing the direct effect ENSO has on VRE generation, and

(ii) studies that analyse the correlation indirectly by looking at meteorological variables instead of electrical generation.

In the following, this section will be divided into studies based on their location: South America, U.S. and Australia.

1.3.1. South America

In [39], Henao et al. study the effects ENSO has on hydropower, solar and wind generation in Colombia. The main motivation of this article is to explore the potential of complimenting different sources of generation, especially during droughts seasons intensified by ENSO. The identified gap that this study attempts to fill is to study the influence ENSO has on solar and wind resources in Colombia. The data has been analysed seasonally due to the behaviour of ENSO, and the complementarity study between variables is done using Pearson’s correlation, as it is one of the most widely accepted measures of complementarity in the literature [42]. Finally, to establish the significance of the correlations a two-tailed t-test is performed.

1.3.2. United States

In [37], Mohammadi et al. analyses the correlation of VRE generation and ENSO in California. The study indirectly assesses this correlation by analysing meteorological variables such as solar radiation, wind speed and precipitation. The article considers different locations in its case study in order to represent the different climate conditions of California. Once the meteorological data is gathered for each location, the data corresponding to ENSO is obtained using the Oceanic Niño Index (ONI), which is a tree-month running mean of the Niño 3.4 index. The National Oceanic and Atmospheric Administration (NOAA) criteria is then used in order to classify the data into the different states of ENSO: El Niño, Neutral or La Niña. Furthermore, each ENSO state is classified into Very Strong, Strong or Moderate scenarios. The main conclusion of this study is the seasonal and regional dependence of the ENSO effect, and that the effects produced by this climate driver are not always similar in all years.

1.3.3. Australia

In [38], Richardson et al. concentrate on the climate influences on renewable energy droughts (mainly compound solar and wind) in Australia. Apart from assessing the effects of ENSO, it also analyses the effects of SAM and the IOD. The study focuses on renewable energy droughts (solar, wind and compound) at a Renewable Energy Zone (REZ) resolution. To evaluate the correlation of VRE droughts with the different climate drivers, the study uses the Niño 3.4 index, the DMI to quantify the IOD and the SAM index.

The main conclusions of this study relating to the climate drivers are:

(i) Widespread solar droughts usually occur during ENSO or SAM events, especially in summer and spring when there are clear La Niña periods. In winter, SAM could be a main modulator of the widespread solar draughts, causing higher than average rainfall in eastern Australia.

(ii) Widespread wind droughts are linked to El Niño periods for all seasons except winter. SAM is believed to not play an important role in wind droughts

(iii) Compound droughts across REZs are found to be linked to both SAM and ENSO for all seasons except for autumn and they peak in spring.

(iv) It is hard to establish a clear link between SAM and widespread droughts although it is also stated that compound droughts are unlikely during negative SAM periods.

(v) There are regional differences related to the frequency of droughts and the effect of ENSO, SAM or SOI. For example, New South Wales and Queensland can experience the greatest effect of solar droughts caused by climate drivers while Tasmania might not see any difference.

(vi) There is a significant resilience of the AEMO grid towards the climate drivers. Even if there are regional dependencies of REZs and climate drivers, the system, as a whole, balances out these variations due to the spatial variability of the climate drivers.

1.4. Summary and Research Question

This chapter summarised the state of the art relating to the three climate drivers relevant to this thesis: ENSO, IOD and SAM. For each one, the characteristics and definition was presented, and the criteria and indices used to measure them was detailed. There was also an emphasis on the effects each climate driver has on Australia.

In the second part of this chapter, a review of the main studies relating VRE generation to each of the climate drivers was presented. Extensive research has been done for the ENSO climate driver correlation with VRE in the U.S. or South America. However, just one article has been found focused on Australia [38]. For the other two climate drivers, a significant gap has been identified relating to the study of their effect on VRE, no matter the location. Again, only Richardson et al. [38] has been found to assess the correlation of SAM and IOD with VRE generation.

In this thesis, we propose to contribute to the identified literature gap relating to the ENSO, SAM and IOD impact towards VRE generation variability in Australia. In this sense, different data, methodologies and spatial resolutions will be implemented to the ones presented by Richardson et al. [38] in order to complement the study and compare the resulting conclusions.

Chapter 2

Impact Analysis of Climate Drivers towards Variable Renewable Energy

2.1. Introduction

This chapter develops the core of the thesis and attempts to answer the research question stated in Section1.4: to study the effects of climate drivers such as ENSO, SAM and IOD have towards VRE generation in Australia.

The first section of this chapter will present the methodology and the data used in the analysis. In the second part, the results will be presented with a visualisation of continuous and discrete correlations of each climate driver and VRE generation source.

2.2. Methodology

In this section, a step-by-step explanation of the methods and data used in the analysis is presented. First of all, the data of the climate drivers and of the VRE generation is explained: its source, its structure, the type of data, etc. A quality assessment has been conducted for each of the sources, modifying and cleaning, in some cases, the original data.

Once all the data has been determined to be suitable for the analysis, Section 2.2.3 describes the methods used in this thesis to determine any correlations between the climate drivers and the VRE generation. Continuous correlations and discrete correlations have been studied and justified. Finally, a statistical significance analysis using Welch's T-test is presented in order to determine whether the observed correlations are significant or not.

2.2.1. Climate Driver Data

As discussed in the Literature Review (Section1.2), the climate drivers used in this study are ENSO, IOD and SAM.

A. ENSO: Multivariate ENSO Index (MEI)

The main advantage of using the MEI index is the number of variables used to calculate the index: while the Niño 3.4 considers only SST, the MEI index considers up to 5 different variables (sea level pressure, SST, surface zonal winds, surface meridional winds and Outgoing Longwave Radiation), as explained in Section 1.2.1. The MEI index is a continuous obtained from [43] and ranging from January 1957 to December 2021.

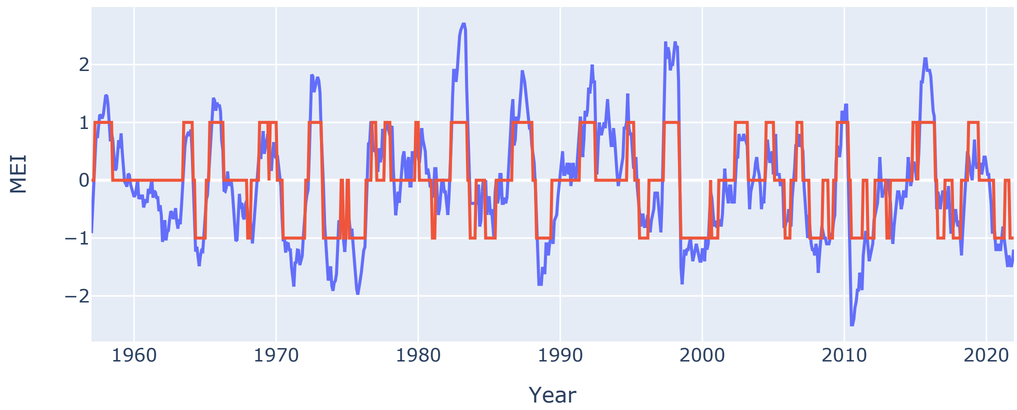
From the continuous MEI, a discrete index is obtained which classifies each period into El Niño (+1), La Niña (-1) or Neutral (0). Figure 19 (a) represents both the continuous and discrete variables associated to ENSO. Table 2 presents the main statistical characteristics of the dataset.

B. IOD: Dipole Mode Index (DMI)

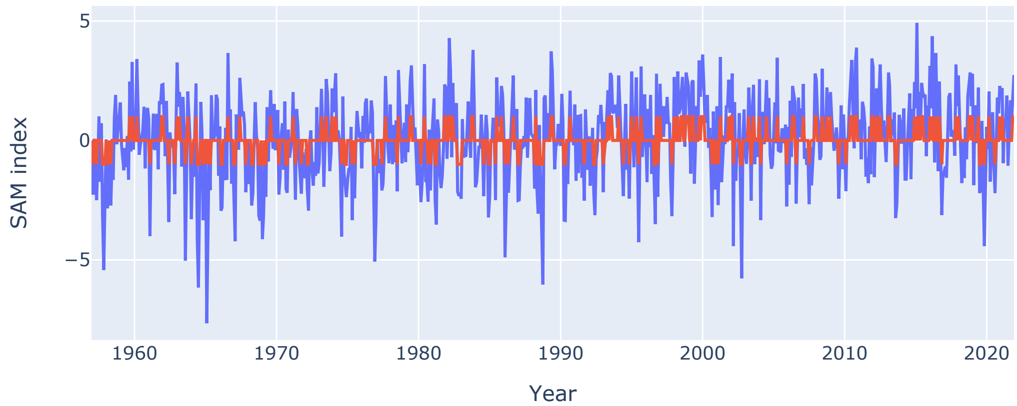
The IOD is measured using the Dipole Mode Index, which represents the difference of SST between the western Indian Ocean and the eastern part (a more detailed description can be found in Section 1.2.221). Figure 19 (b) represents the continuous DMI and the discrete clasiffication of the climate driver. Similarly to the previous section, Table 2 shows the main statistical characteristics of this index.

C. SAM: Marshall SAM index

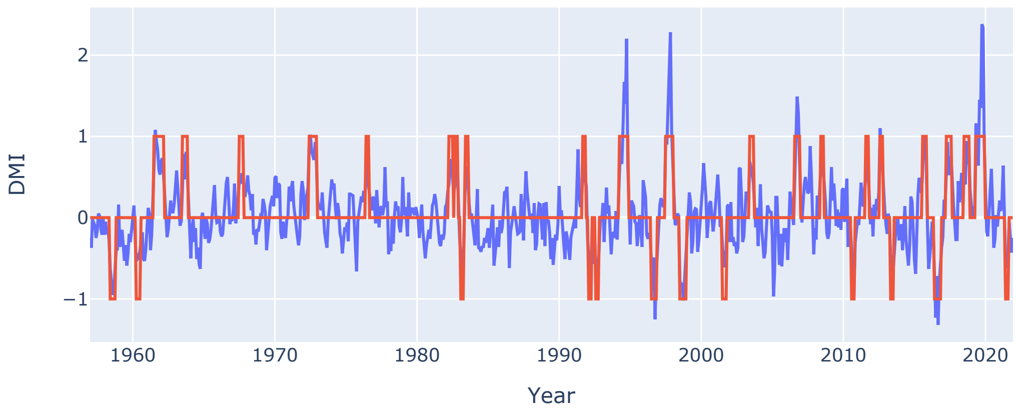
As was explained in Section 1.2.3, there are many different indices to measure SAM events. For this study the Marshall SAM index has been selected mainly due to its long timespan, ranging from 1957 to present. Figure 19 (c) represents the continuous and discrete variables associated to historical SAM events. On the other hand, Table 2 presents the statistical characteristics of this index.



(a) Multivariate ENSO Index



(b) Marshall SAM Index



(c) Dipole Mode Index for SOI

Figure 19 – Continuous (blue) and discrete (red) variables for each of the three climate drivers. Source: Author.

Table 2 - Statistical Description of climate driver data.

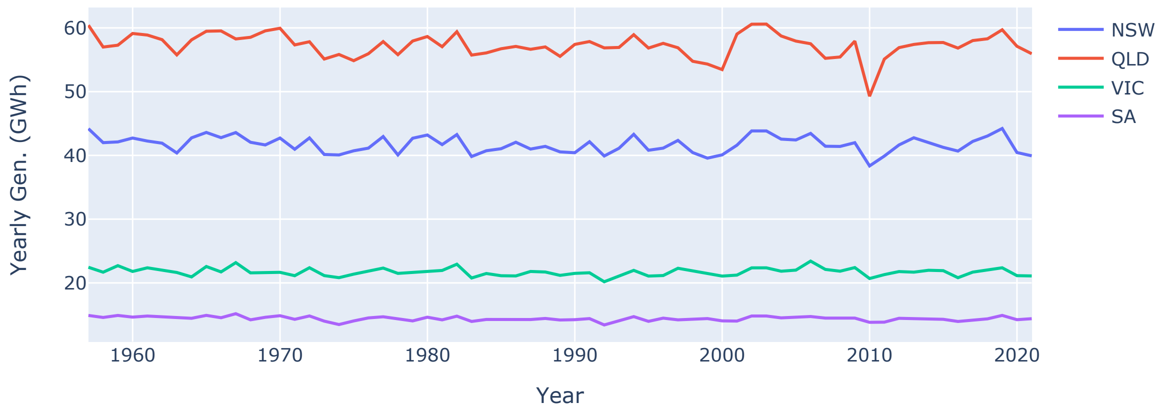
	MEI	DMI	SAM Index
Count	780	780	780
Mean	-0.07	0.05	0.06
Standard Dev.	0.95	0.45	1.79
Minimum	-2.50	-1.32	-7.65
25 Percentile	-0.72	-0.24	-1.12
50 Percentile	-0.10	0.02	0.12
75 Percentile	0.51	0.28	1.35
Maximum	2.70	2.38	4.92

2.2.2. VRE Generation Data

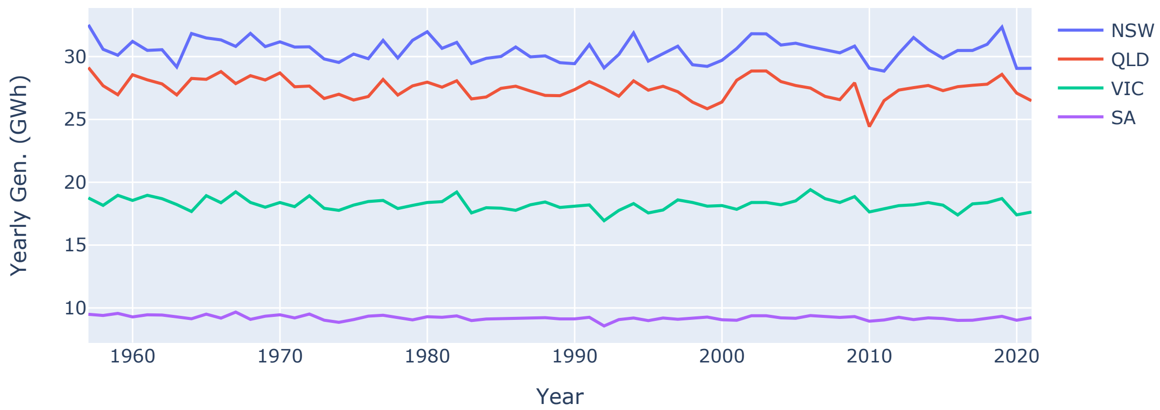
The data relating to historical VRE generation has been produced internally by Iberdrola Australia. The capacity of each source is based on the ISP 2050 Step-Change mainland VRE build. In order to simulate historical data (since January 1957), ERA5 meteorological data has been used to back-trace VRE generation with a fixed capacity of each renewable source.

The data is divided into three VRE sources: Large scale solar power, wind power and rooftop solar power. For each source, the data is geographically divided into four states: New South Wales (NSW), Queensland (QLD), Victoria (VIC) and South Australia (SA). This will allow for a regional analysis of the climate drivers and the effect they have on VRE generation in each state of the NEM.

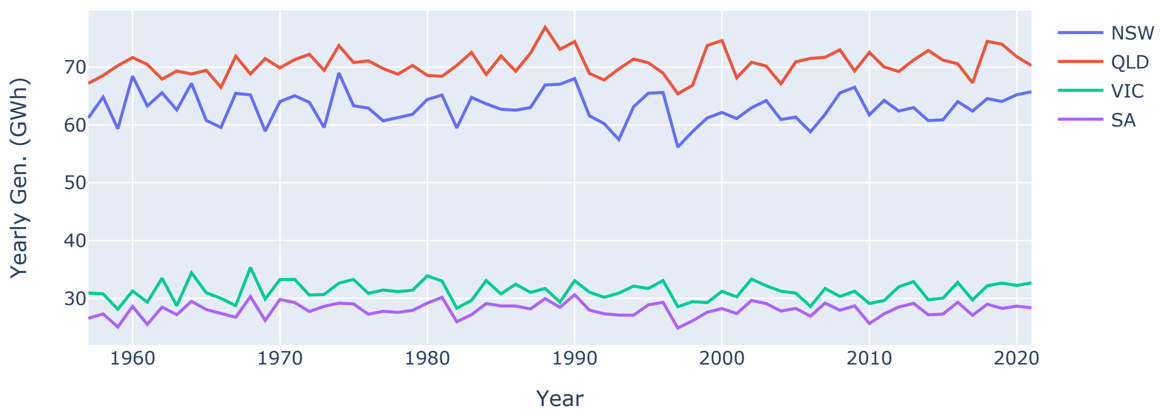
In Figure 20, the yearly generation of each trace and for each state is presented. As can be seen, each state has a different capacity with QLD generally being the state with higher RE capacity (except for rooftop), and SA being the state with the smallest capacity. On the other hand, it is clear that the annual variation in generation between states follows similar trends although not exact, due to the regional variations in weather between states.



(a) Solar Generation



(b) Rooftop Generation



(c) Wind Generation

Figure 20 – Yearly generation (GWh) of the renewable traces for each source and state. Source: Author.

For clarity, Figure 20 is shown in a yearly resolution. However, the resolution used for the analysis will be in a weekly scale. Figure 21 shows the weekly solar generation for a given year (2014).

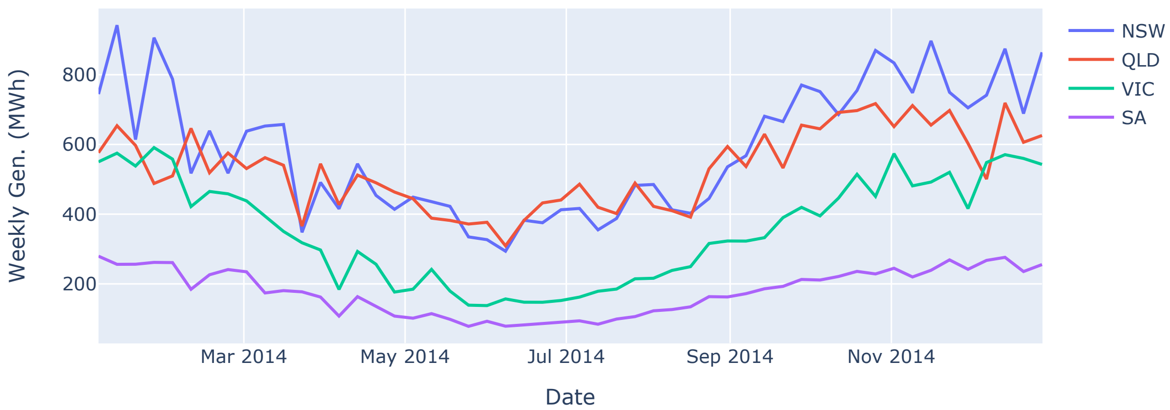


Figure 21 - Weekly solar generation in 2014. Source: Author

A clear seasonal trend is observed in Figure 21, which poses a problem when wanting to determine the effects climate drivers have. Therefore, cancel out seasonal variations a typical mean year is constructed for each trace. This is obtained by taking, for every hour of that year, the average of all datapoints relating to that specific hour. Formulated mathematically, for each hour h in the typical mean year,

$$E_{TMY,h} = \frac{\sum_{i=0}^{N} E_{h,i}}{N}$$

where, $E_{TMY,h}$ is the generation of a single hour (h) in the typical mean year,
$E_{h,i}$ is the generation of the hour h for the year i,
N is the number of years in the dataset.

Therefore, the typical mean year of each trace and for each state is obtained. Once the average years are obtained, in order to supress seasonal variations, the hourly generation is divided by the typical mean year generation corresponding to each hour. Mathematically, for each hour h in the dataset,

$$E'_h = \frac{E_h}{E_{TMY,h}}$$

where, E'_h is the new dimensionless trace data without seasonal variations,
E_h is the original trace generation for hour h in the dataset.

To clarify this section, Figure 22 shows the typical mean year of a given period together with the original trace data in a weekly resolution. By dividing each component of these two graphs, the dimensionless trace data without seasonal variation is obtained, as can be seen in

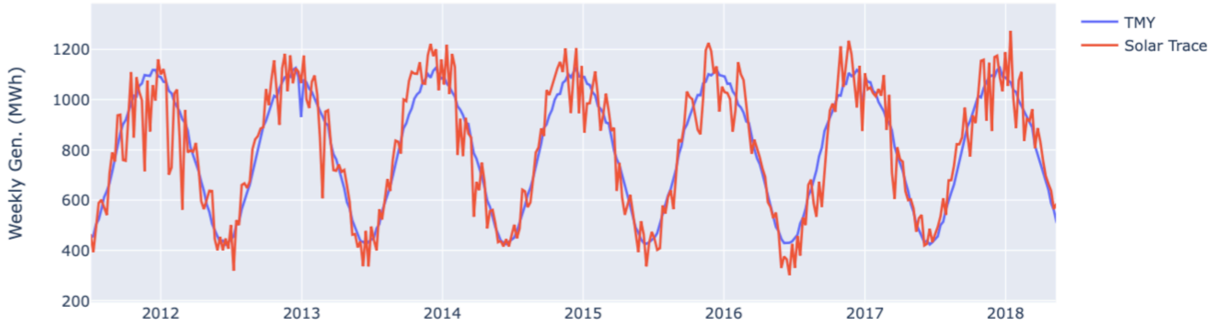


Figure 22 - Typical mean year generation (blue) and original weekly generation (red) for NSW solar trace. Source: Author.

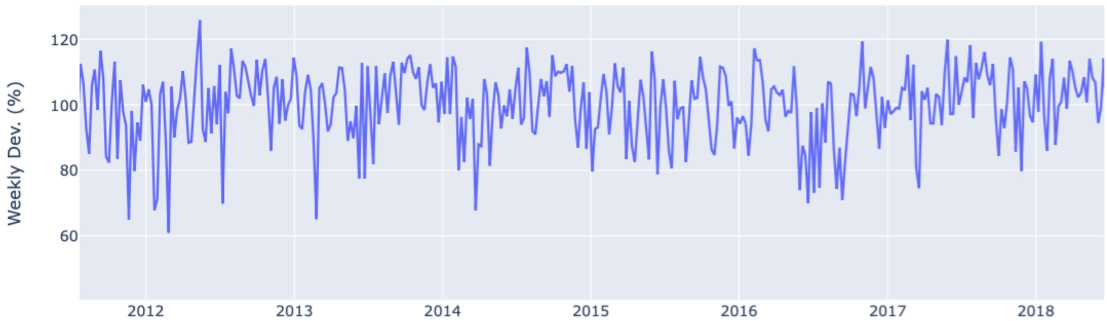


Figure 23 - Weekly deviation in solar generation for NSW. Source: Author.

As mentioned above, the new variables without seasonal trends are dimensionless and represent the deviation between the real generation for a specific time instance and the average generation for that specific time instance corresponding to the typical mean year. It is expressed as a percentage, where:

- Values above 100 % represent an above-average generation with respect to the typical mean year.
- Values equal 100 % represent a generation equal to the expected average generation of a given time instance.
- Values bellow 100 % represent bellow-average generation for a given time instance.

Not all traces and deviations are represented in order to facilitate the reading of this study. However, once all the deviations have been obtained, the correlation analysis can be commenced.

2.2.3. Correlation Analysis

The correlation analysis will attempt to determine the links between the climate drivers and the normalised generation traces

As there are two sets of data for each climate driver (continuous and discrete), the correlation study will perform two different types of analysis:

(i) The continuous analysis, by visualising two variables in a scatter plot and determining their correlation coefficient. The results are shown in Section 2.3.

(ii) The discrete correlation analysis, each trace is represented into boxplots divided according to the discrete climate driver variable. The results of this analysis can be found in Section 2.4.

Note: in order to study the correlation between climate drivers and VRE generation, a 4-week lag has been adopted between the climate driver changing state and VRE generation noticing such an effect. This 4-week lag is not arbitrary, and it is adopted by various studies [43] [44].

2.2.4. Statistical Significance Analysis

Finally, the last part of the analysis in the impact of climate drivers towards VRE generation, is to do a statistical significance test of the results obtained in the previous section.

For the discrete correlation analysis, the Welch's T-test is performed. The main assumptions to this test are:

- The predictor variable is categorical (i.e. discrete). This corresponds to the discrete climate driver data.
- The outcome variable is continuous. This corresponds to the normalised trace data.
- There are two possible sets: positive and negative states of the climate drivers (the neutral state is omitted)
- The variances between data sets are the same.
- The chosen statistical threshold is 0.05.

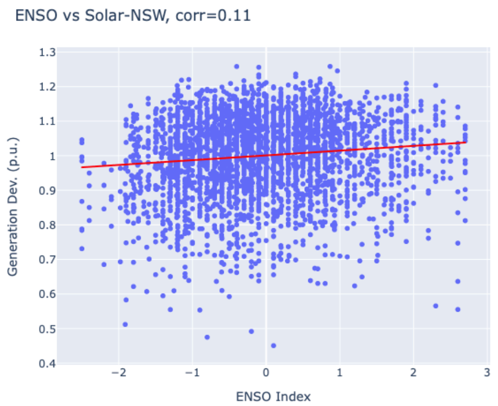
The results of the significance tests are combined in Section 2.4, with the box plots. The full results can be viewed in Annex I.

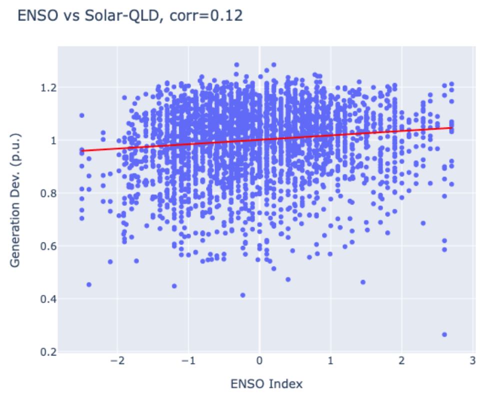
In the following sections, the results obtained by applying the methods described previously are shown. In the following section, the continuous scatter plots of each trace, climate driver and state are presented. In Section 2.4, the discrete variables of the climate drivers are used, and box plots are obtained for each trace, climate driver and state.

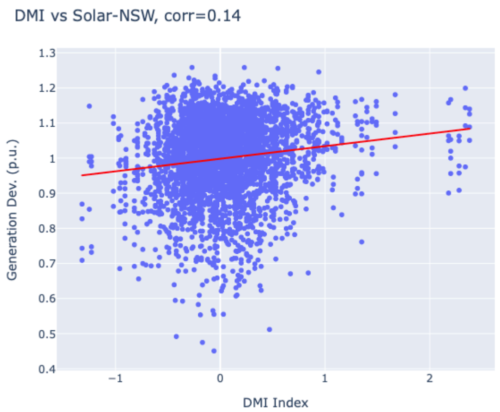
2.3. Results. Continuous Correlation

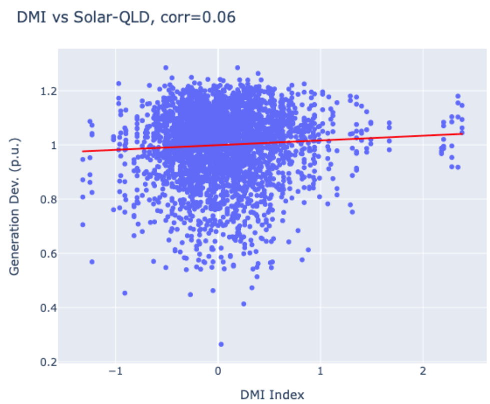
In the first part of the results, the continuous scatter plots of each trace, climate driver and state are presented

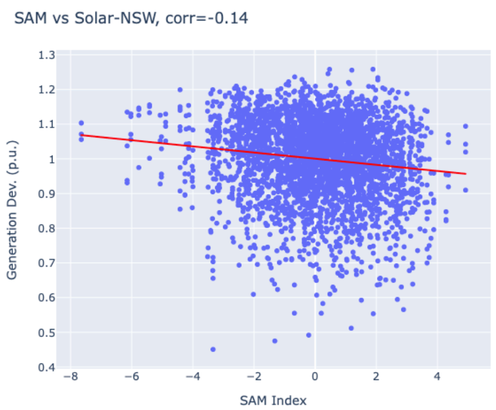
2.3.1. Solar Trace

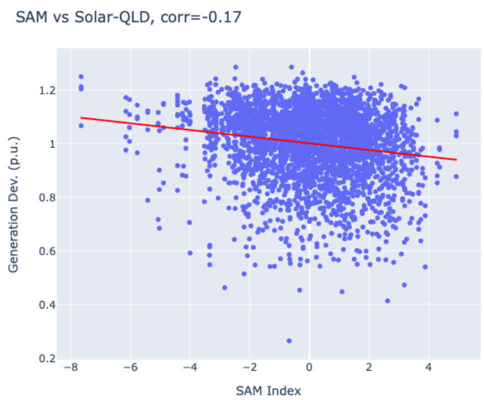


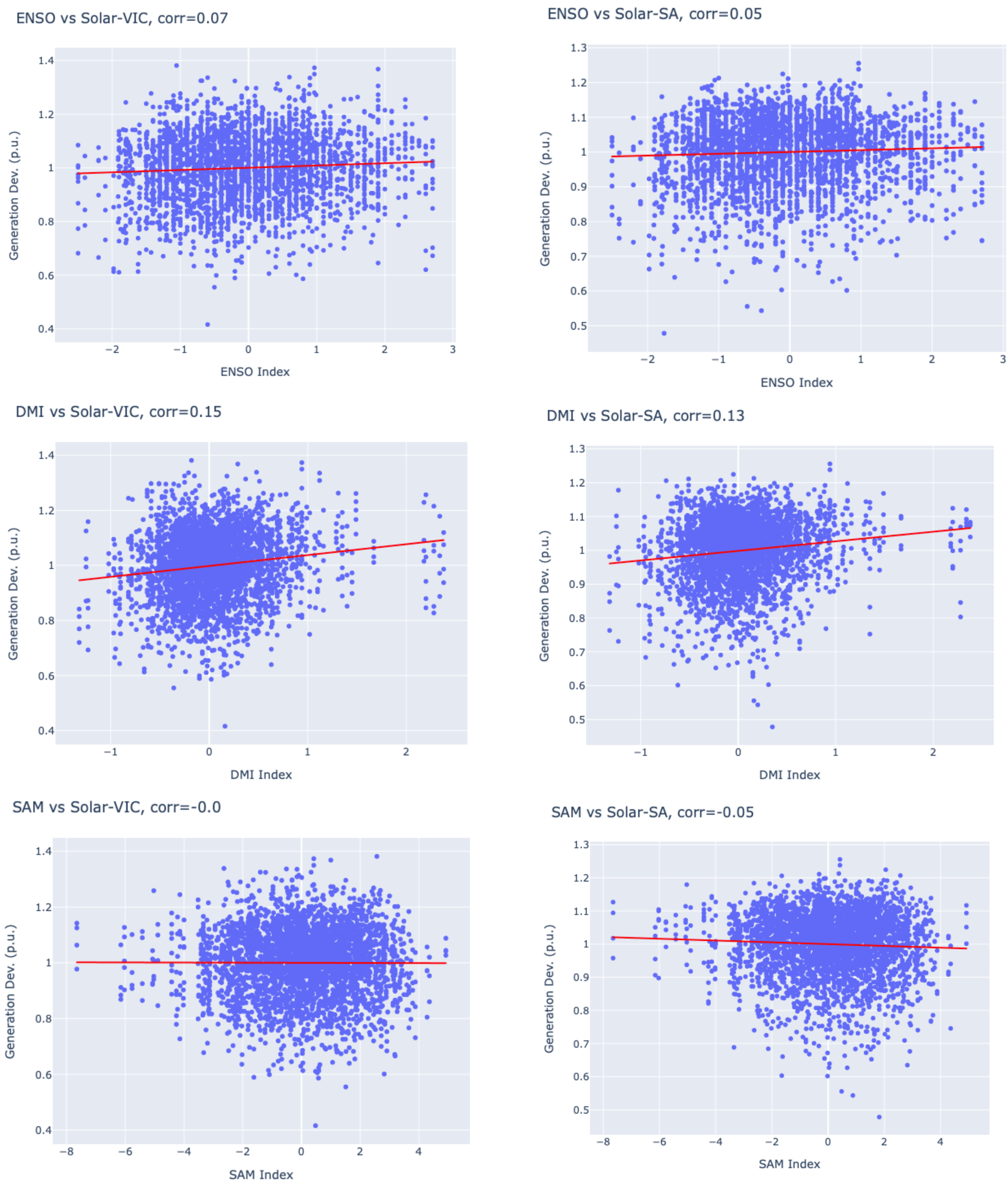




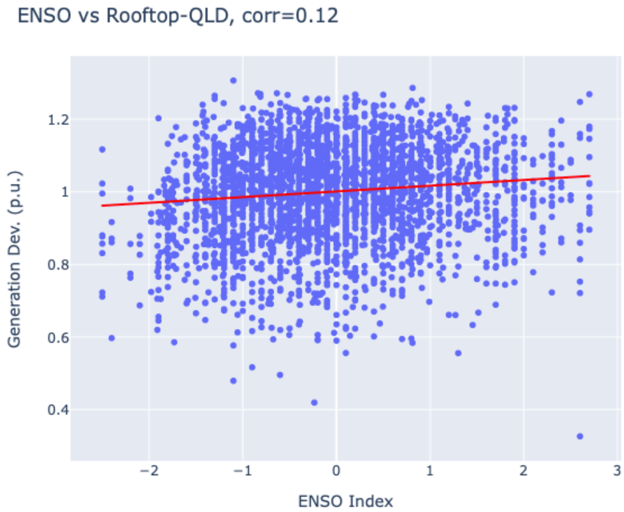


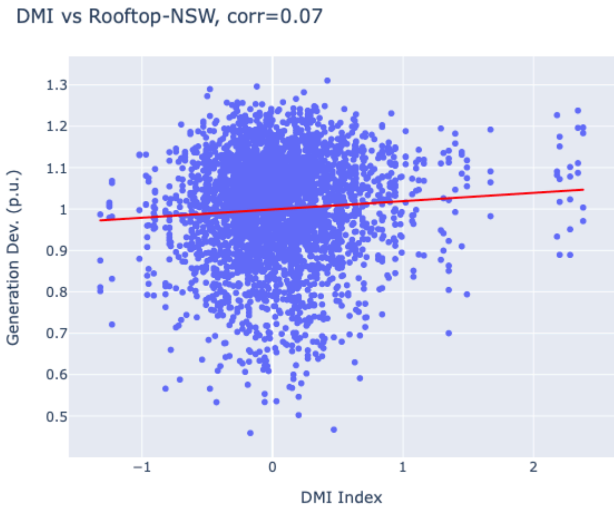


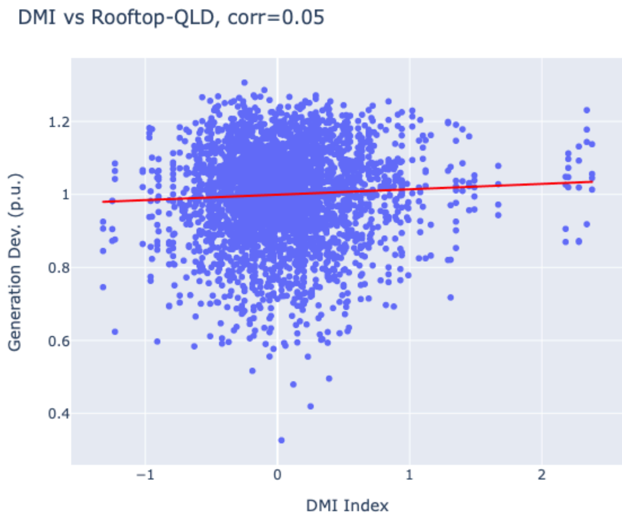


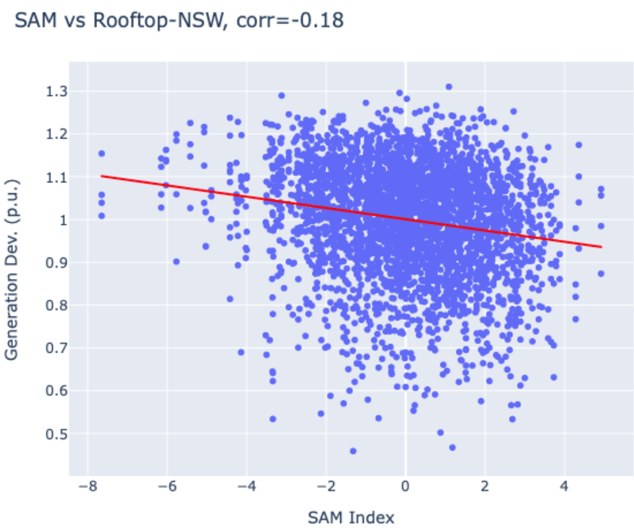

ENSO vs Solar-VIC, corr=0.07
Generation Dev. (p.u.)
ENSO Index
ENSO vs Solar-SA, corr=0.05
Generation Dev. (p.u.)
ENSO Index
DMI vs Solar-VIC, corr=0.15
Generation Dev. (p.u.)
DMI Index
DMI vs Solar-SA, corr=0.13
Generation Dev. (p.u.)
DMI Index
SAM vs Solar-VIC, corr=-0.0
Generation Dev. (p.u.)
SAM Index
SAM vs Solar-SA, corr=-0.05
Generation Dev. (p.u.)
SAM Index

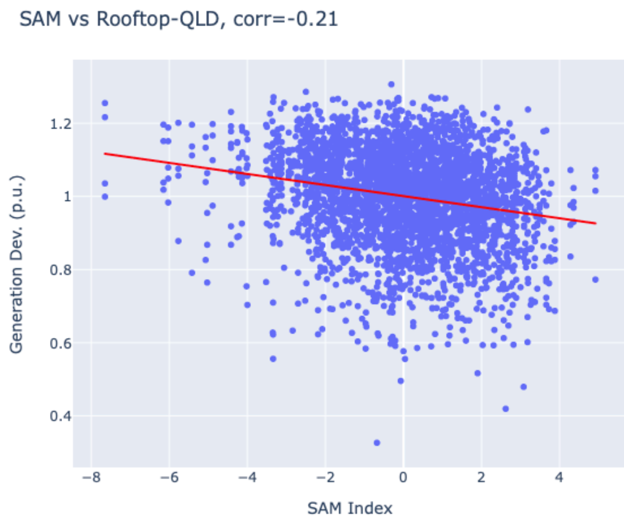
2.3.2. Rooftop Trace

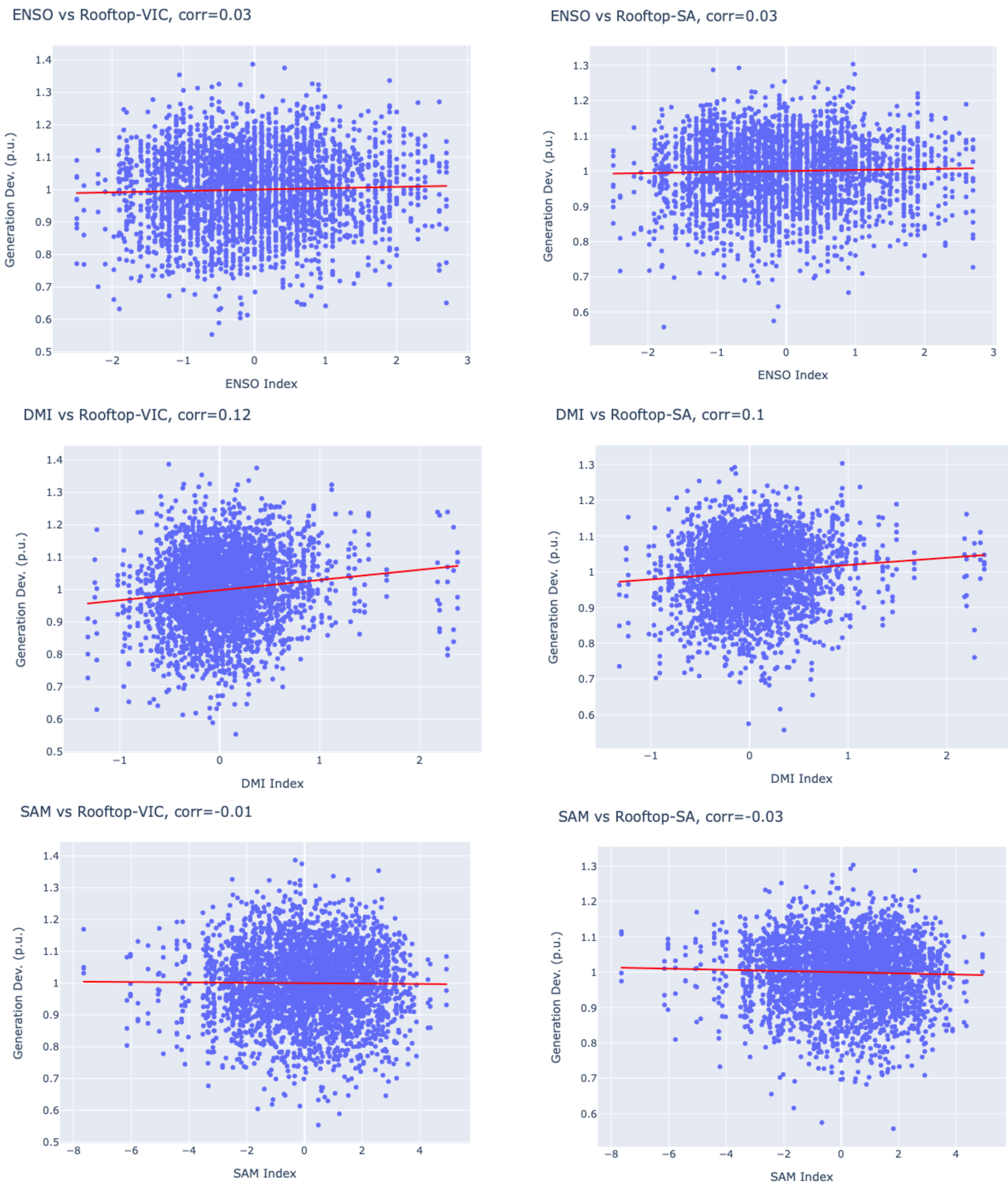




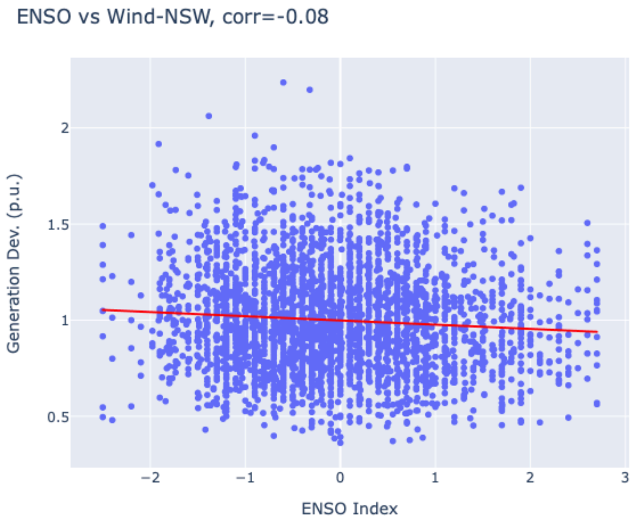


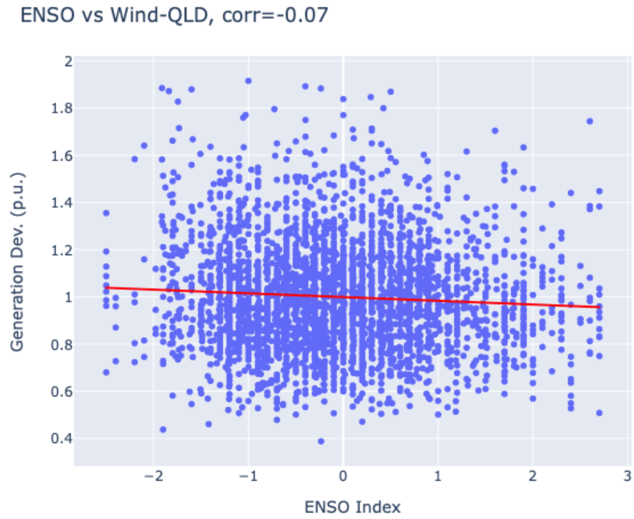


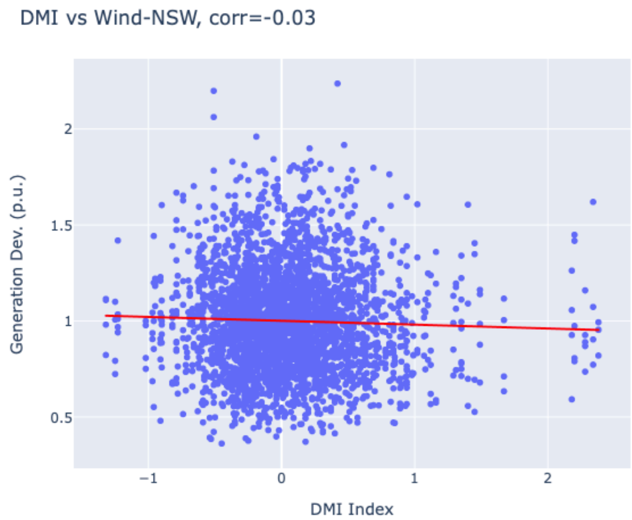


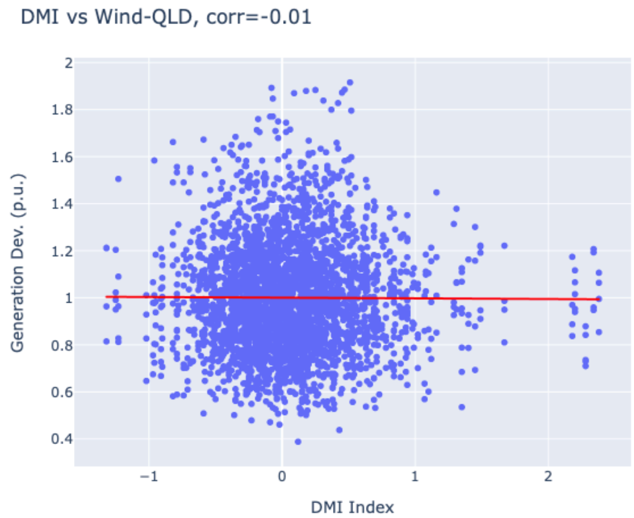

ENSO vs Rooftop-VIC, corr=0.03
ENSO vs Rooftop-SA, corr=0.03
DMI vs Rooftop-VIC, corr=0.12
DMI vs Rooftop-SA, corr=0.1
SAM vs Rooftop-VIC, corr=-0.01
SAM vs Rooftop-SA, corr=-0.03
Generation Dev. (p.u.)
ENSO Index
DMI Index
SAM Index

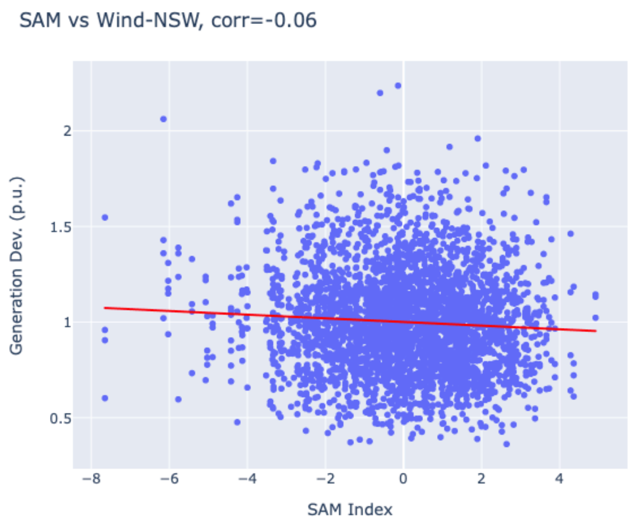
2.3.3. Wind Trace

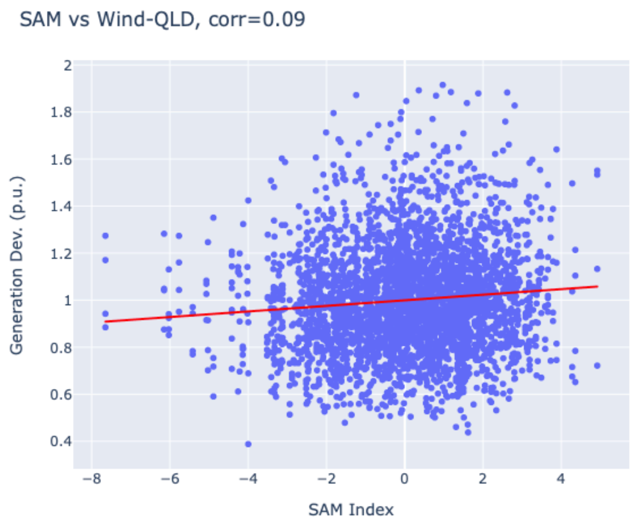


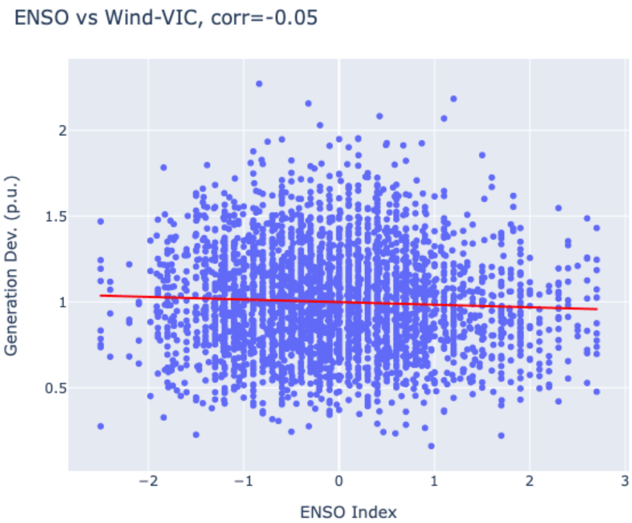


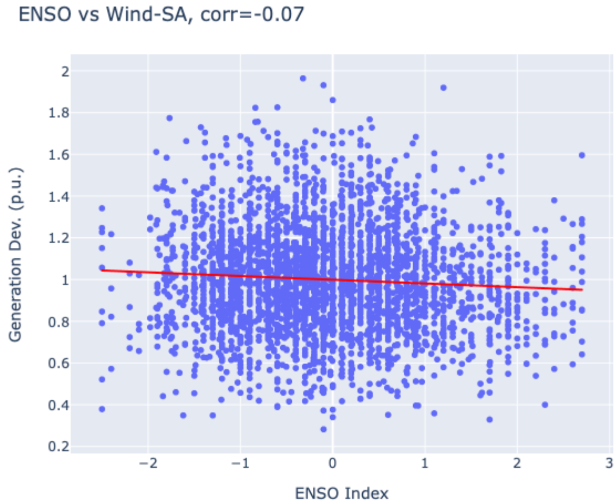


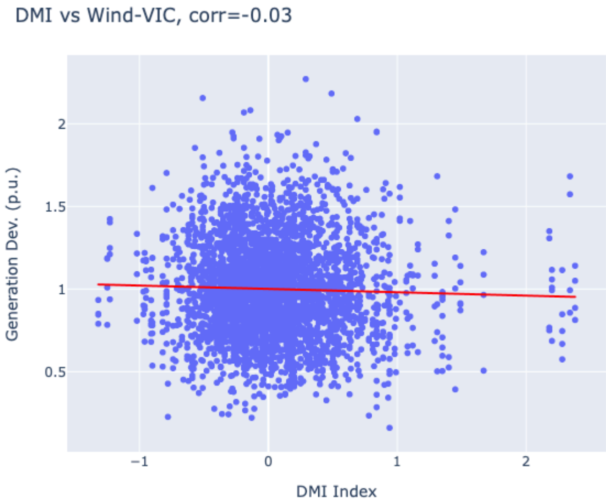


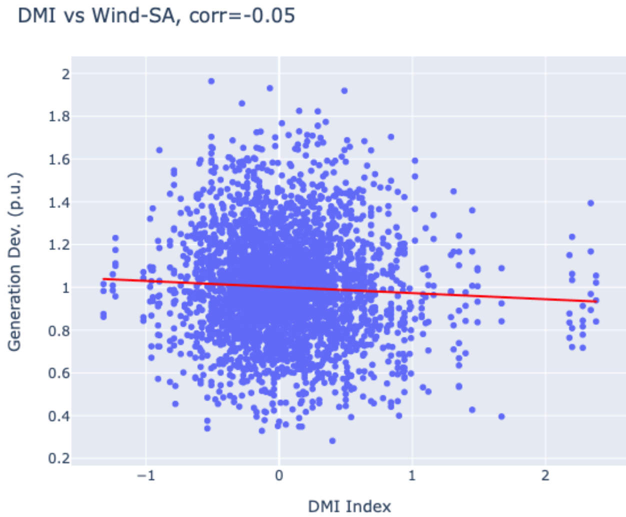


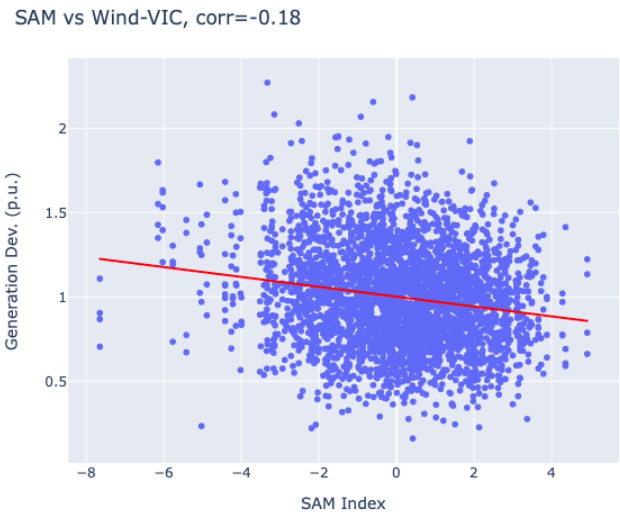


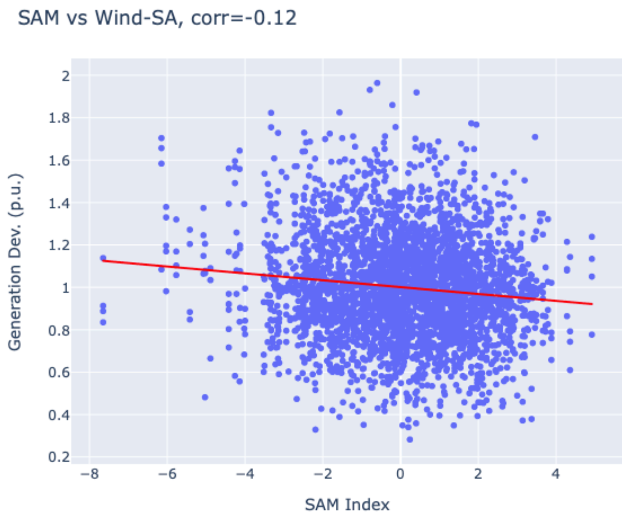

ENSO vs Wind-VIC, corr=-0.05
Generation Dev. (p.u.)
ENSO Index


ENSO vs Wind-SA, corr=-0.07
Generation Dev. (p.u.)
ENSO Index


DMI vs Wind-VIC, corr=-0.03
Generation Dev. (p.u.)
DMI Index


DMI vs Wind-SA, corr=-0.05
Generation Dev. (p.u.)
DMI Index

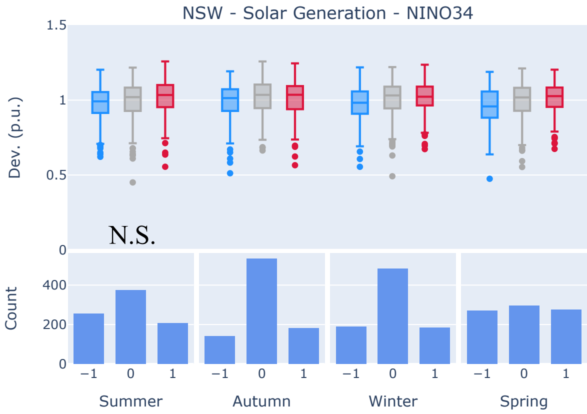

SAM vs Wind-VIC, corr=-0.18
Generation Dev. (p.u.)
SAM Index

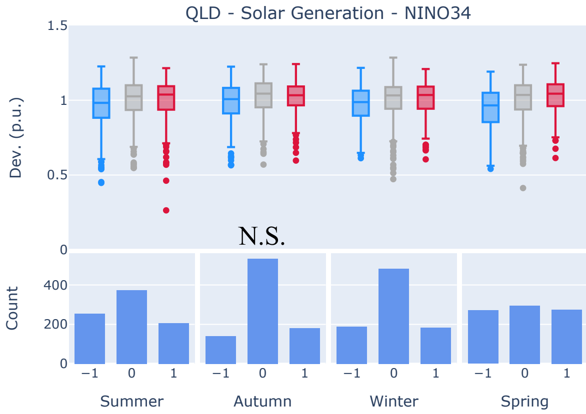

SAM vs Wind-SA, corr=-0.12
Generation Dev. (p.u.)
SAM Index

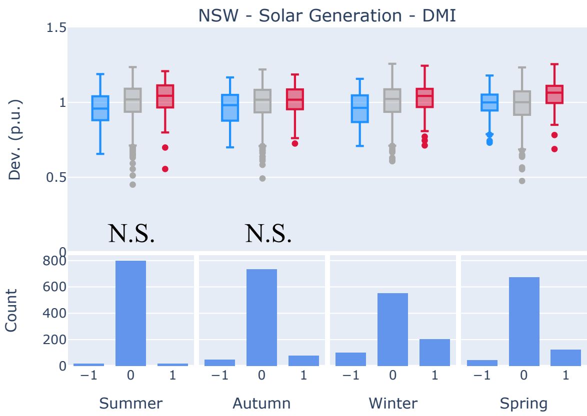
2.4. Results. Discrete Correlation

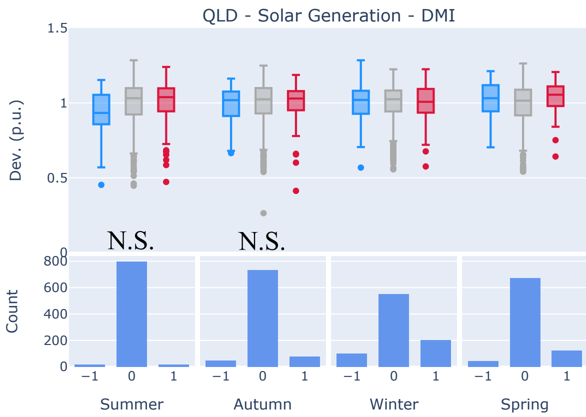
In this second part of the results, the discrete variables of the climate drivers are used, and box plots are obtained for each trace, climate driver and state.

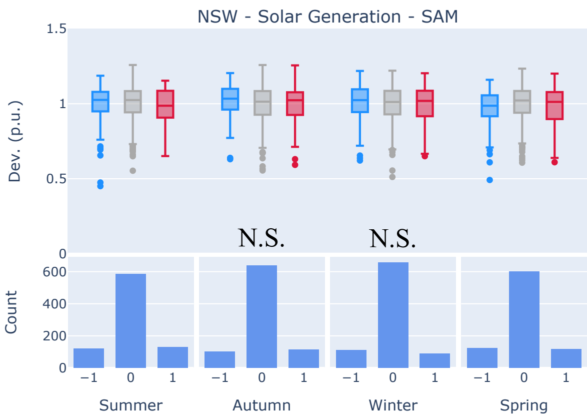
2.4.1. Solar Trace

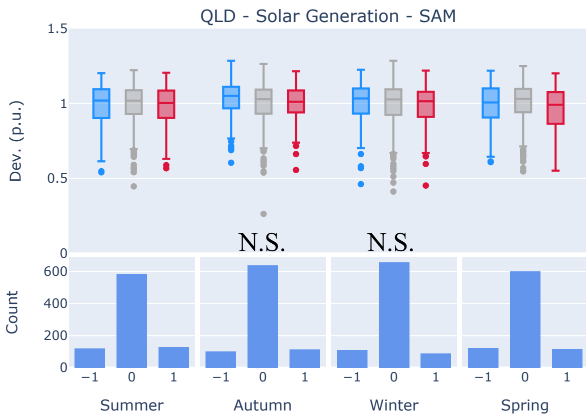


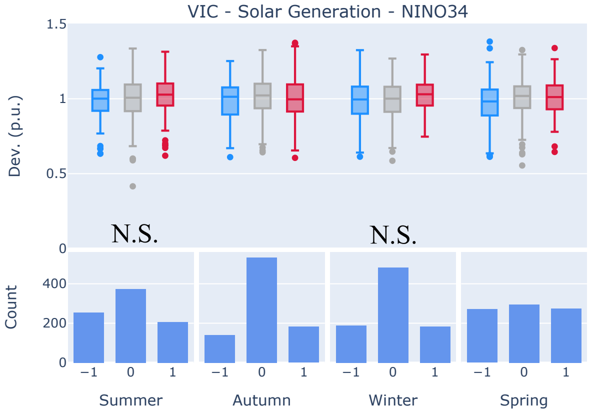


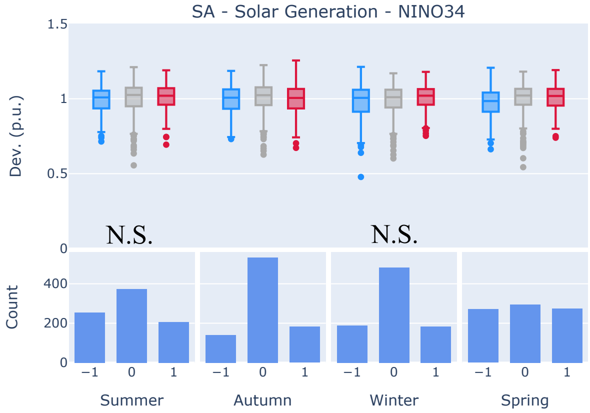


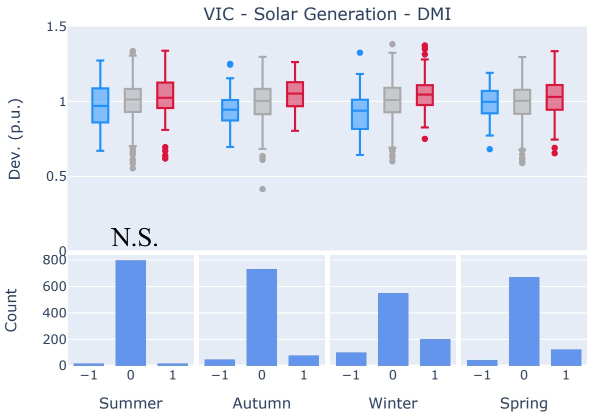


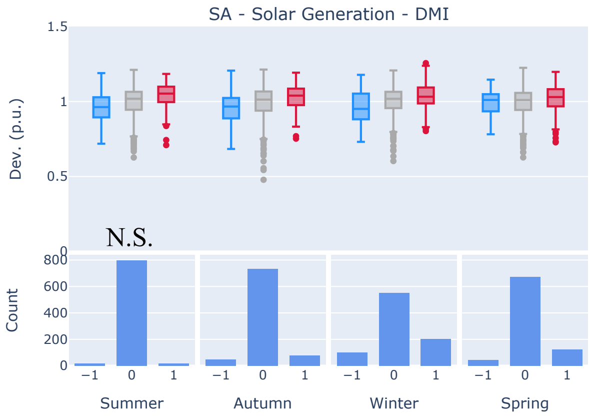


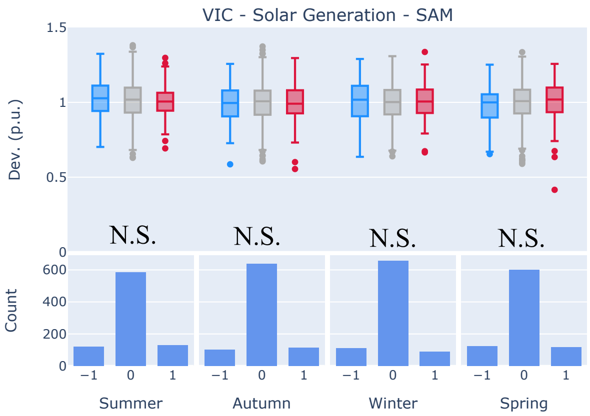


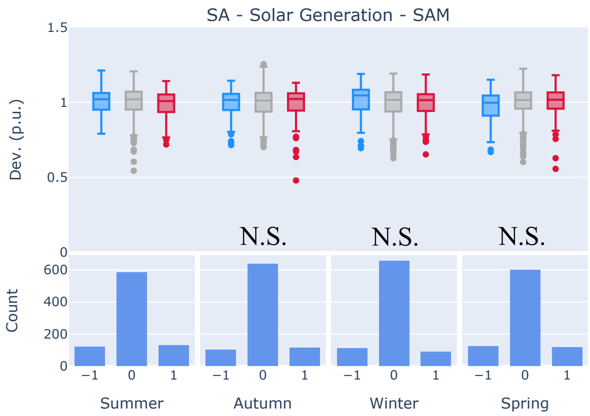

VIC - Solar Generation - NINO34
Dev. (p.u.)
Count
N.S.
N.S.
Summer
Autumn
Winter
Spring


SA - Solar Generation - NINO34
Dev. (p.u.)
Count
N.S.
N.S.
Summer
Autumn
Winter
Spring

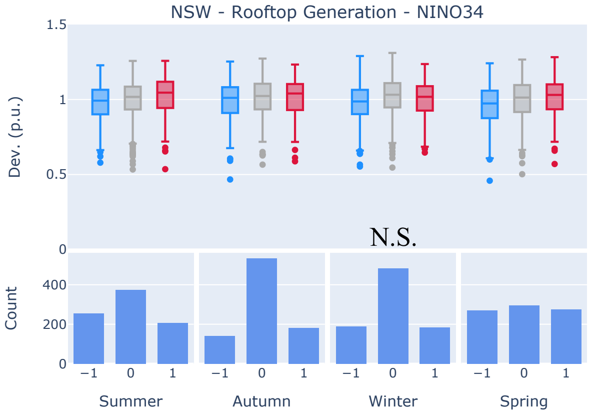

VIC - Solar Generation - DMI
Dev. (p.u.)
Count
N.S.
Summer
Autumn
Winter
Spring

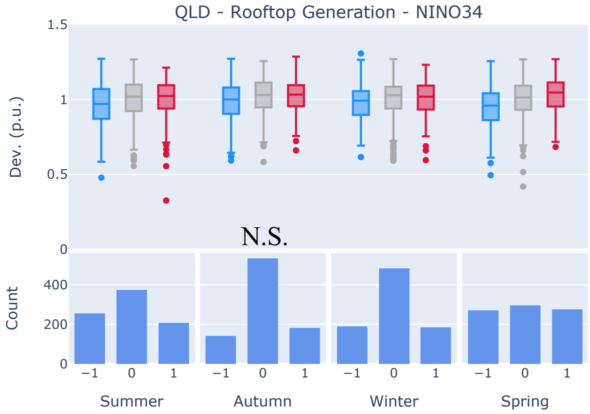

SA - Solar Generation - DMI
Dev. (p.u.)
Count
N.S.
Summer
Autumn
Winter
Spring

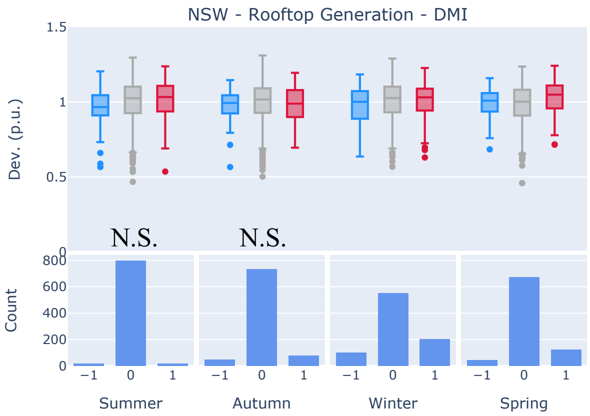

VIC - Solar Generation - SAM
Dev. (p.u.)
Count
N.S.
N.S.
N.S.
N.S.
Summer
Autumn
Winter
Spring

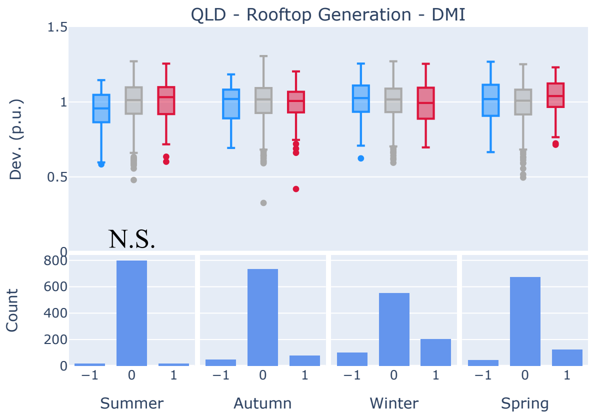

SA - Solar Generation - SAM
Dev. (p.u.)
Count
N.S.
N.S.
N.S.
Summer
Autumn
Winter
Spring

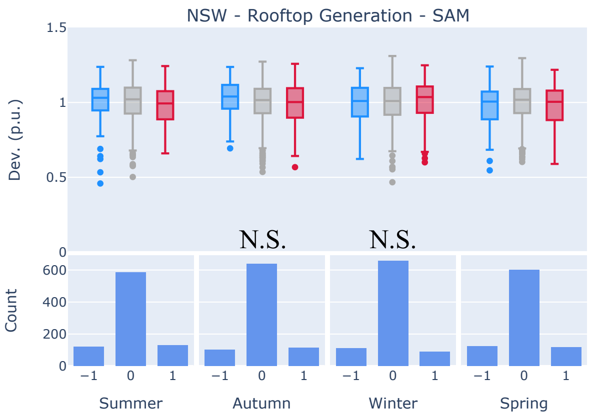
2.4.2. Rooftop Trace

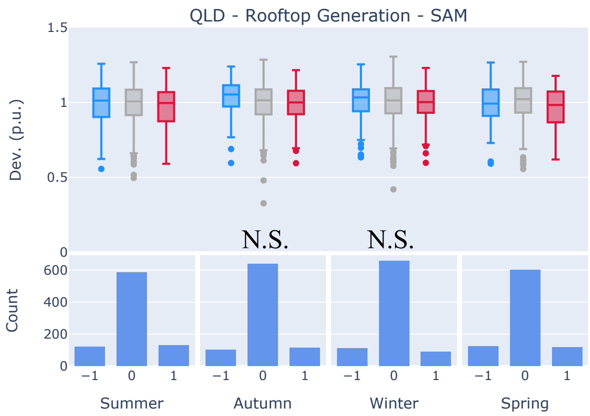


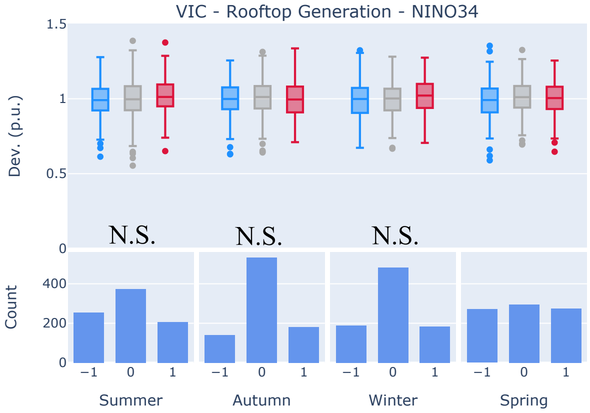


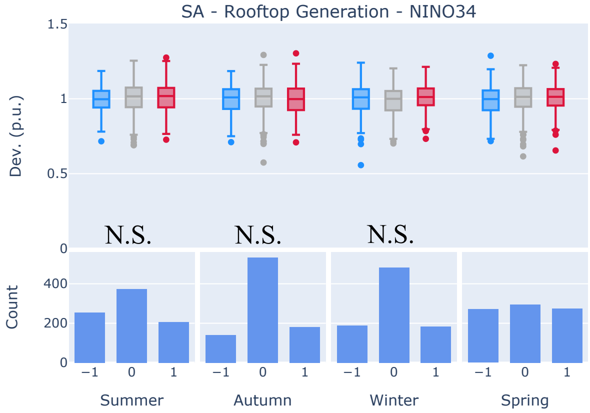


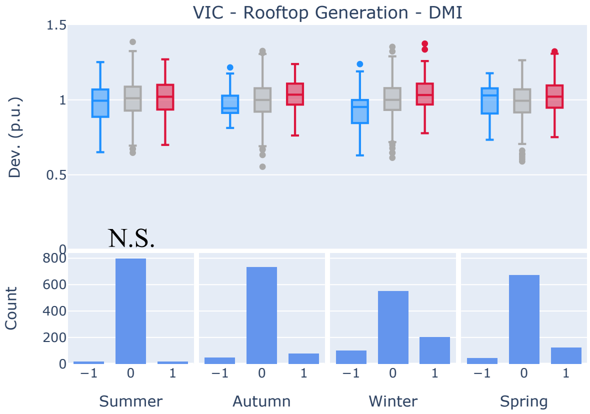


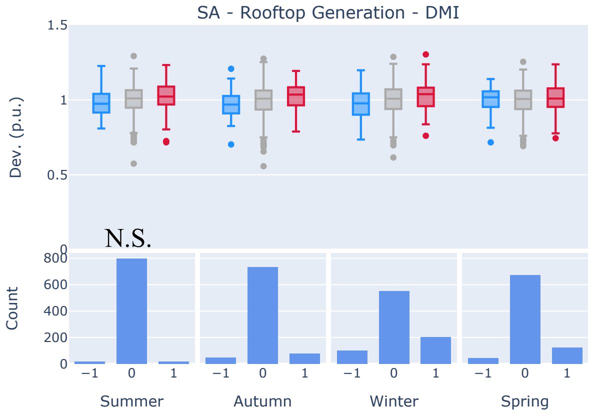


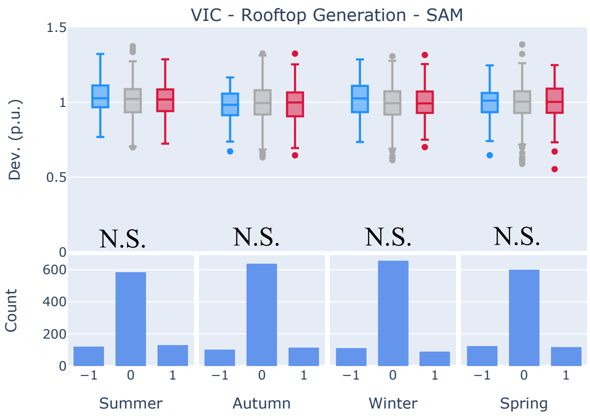


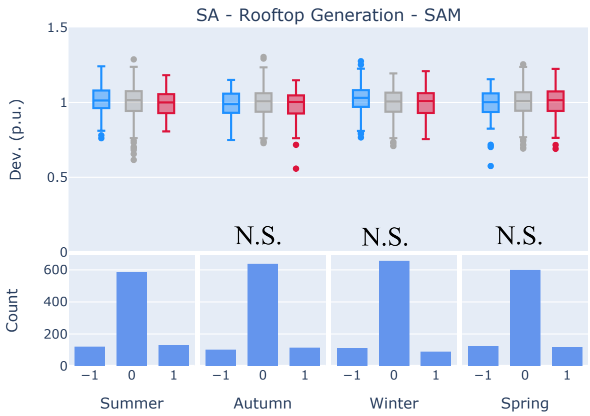

VIC - Rooftop Generation - NINO34
Dev. (p.u.)
Count
N.S.
N.S.
N.S.
Summer
Autumn
Winter
Spring


SA - Rooftop Generation - NINO34
Dev. (p.u.)
Count
N.S.
N.S.
N.S.
Summer
Autumn
Winter
Spring

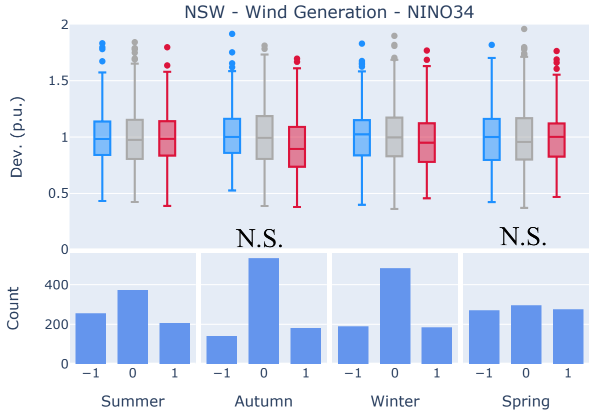

VIC - Rooftop Generation - DMI
Dev. (p.u.)
Count
N.S.
Summer
Autumn
Winter
Spring

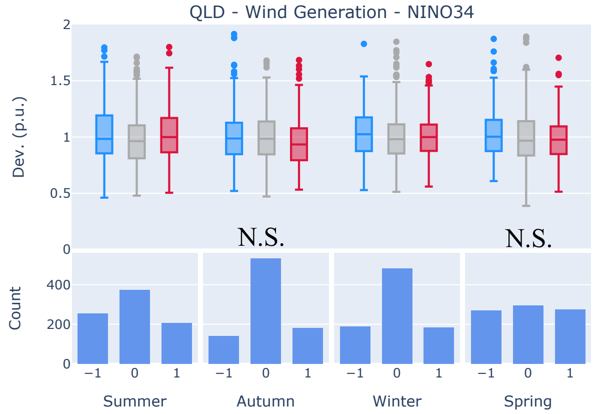

SA - Rooftop Generation - DMI
Dev. (p.u.)
Count
N.S.
Summer
Autumn
Winter
Spring

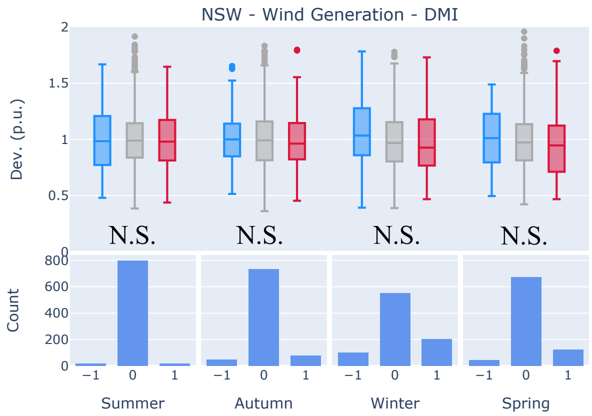

VIC - Rooftop Generation - SAM
Dev. (p.u.)
Count
N.S.
N.S.
N.S.
N.S.
Summer
Autumn
Winter
Spring

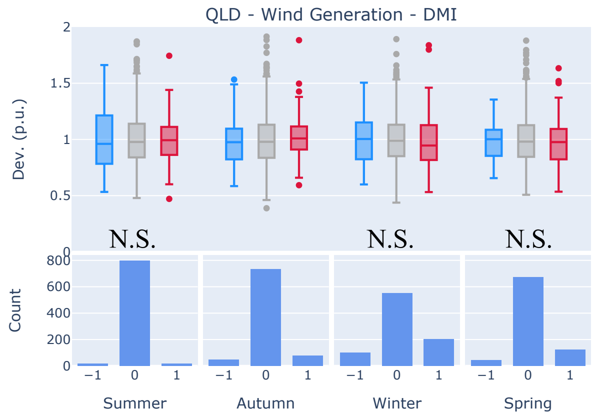

SA - Rooftop Generation - SAM
Dev. (p.u.)
Count
N.S.
N.S.
N.S.
Summer
Autumn
Winter
Spring

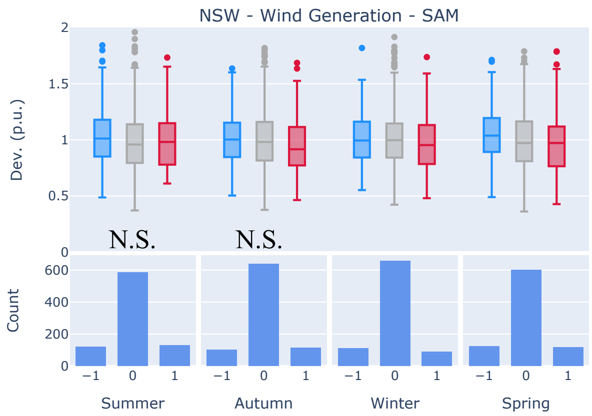
2.4.3. Wind Trace

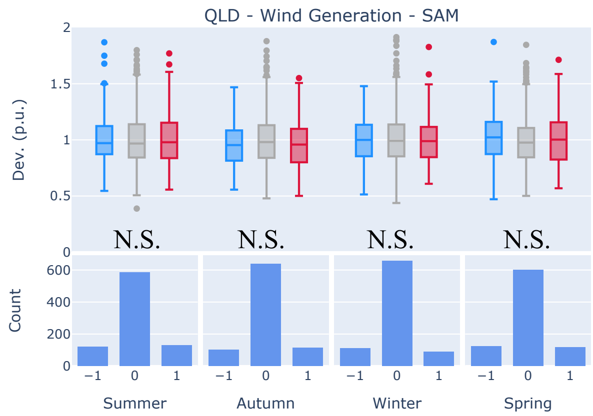


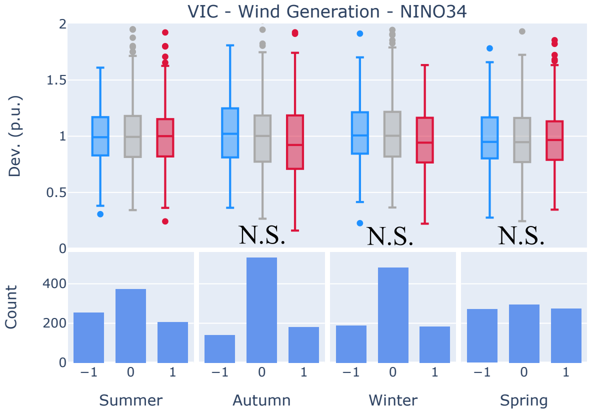


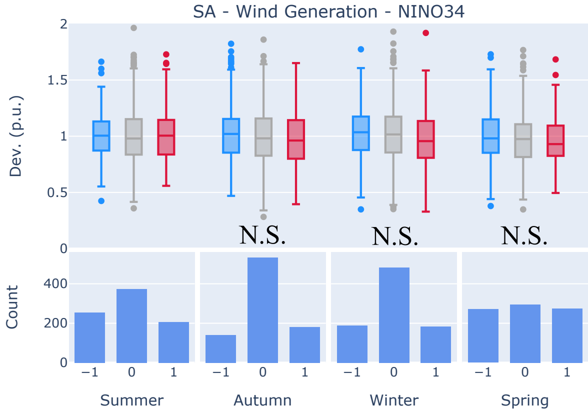


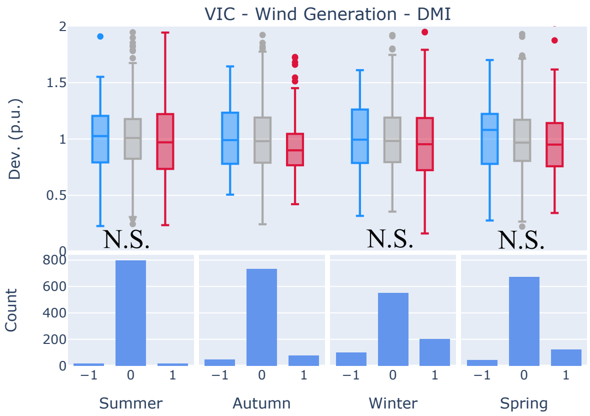


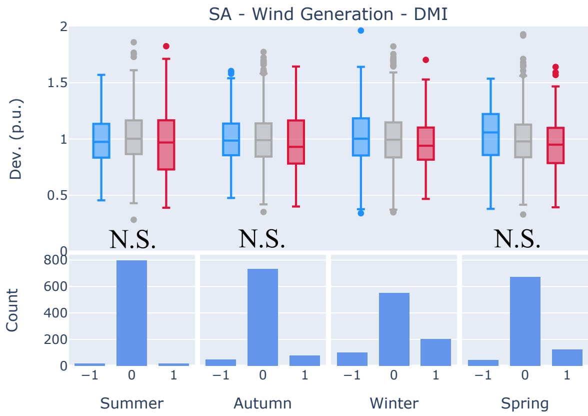


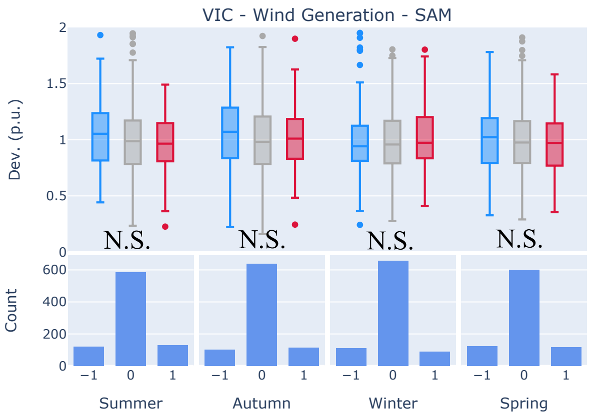


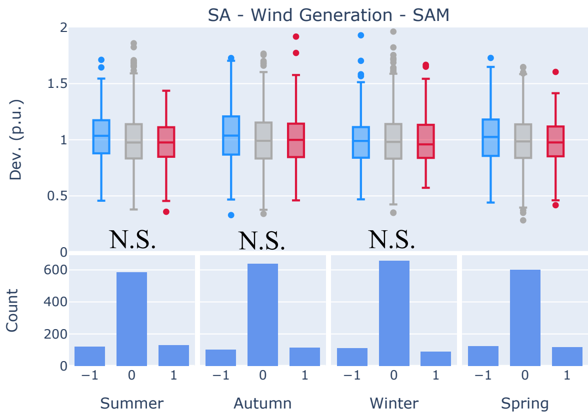

VIC - Wind Generation - NINO34
Dev. (p.u.)
Count
N.S.
N.S.
N.S.
Summer
Autumn
Winter
Spring


SA - Wind Generation - NINO34
Dev. (p.u.)
Count
N.S.
N.S.
N.S.
Summer
Autumn
Winter
Spring


VIC - Wind Generation - DMI
Dev. (p.u.)
Count
N.S.
N.S.
N.S.
Summer
Autumn
Winter
Spring


SA - Wind Generation - DMI
Dev. (p.u.)
Count
N.S.
N.S.
N.S.
Summer
Autumn
Winter
Spring


VIC - Wind Generation - SAM
Dev. (p.u.)
Count
N.S.
N.S.
N.S.
N.S.
Summer
Autumn
Winter
Spring


SA - Wind Generation - SAM
Dev. (p.u.)
Count
N.S.
N.S.
N.S.
Summer
Autumn
Winter
Spring

2.5. Summary

In this chapter the methodology and results of the analysis have been presented. First of all, the data was visualised and the steps to process it were shown for both the climate drivers and the VRE traces Secondly, the correlation analysis was explained for both continuous variables (climate driver indices) and discrete variables (climate driver states). Next, the statistical significance calculations were explained where Welch's t-test was implemented. Finally, the results of both discrete and continuous correlations were presented, with the correlation coefficients and the statistical significance results shown.

Chapter 3
Discussion

In this chapter a discussion is presented about the implications of the results obtained in the previous sections, and the objectives and further gaps of thesis.

3.1. Discussion on the Results

This section focuses on the results obtained in Sections 2.3 and 2.4. First of all, from the discrete analysis, a quantification of the statistically significant results will be grouped in tables.

3.1.1. Quantification of statistically significant results

For each VRE trace, the results of the discrete correlation analysis is presented in the following tables. The quantification of the results is based on the mean of the generation deviation. For simplicity, the following convention has been adopted:

- Values > 0 %: the generation is above expected (average) historical levels.
- Values ≈ 0 %: the generation is equal or near to expected historical levels.
- Values < 0 %: the generation is below expected historical levels.

Table 3 - Results from discrete correlation of climate drivers to SOLAR generation.

ENSO								
	Summer		Autumn		Winter		Spring	
	Neg.	Pos.	Neg.	Pos.	Neg.	Pos.	Neg.	Pos.
NSW	N.S.		1%	3%	-2%	+2%	-5%	+3%
QLD	-2%	+4%	N.S.		-2%	+3%	-4%	+4%
VIC	N.S.		+1%	-1%	N.S.		-2%	+1%
SA	N.S.		1%	0%	N.S.		-2%	2%
DMI								
	Summer		Autumn		Winter		Spring	
	Neg.	Pos.	Neg.	Pos.	Neg.	Pos.	Neg.	Pos.
NSW	N.S.		N.S.		-4%	+4%	0%	+6%
QLD	N.S.		N.S.		+2%	0%	+3%	+5%
VIC	N.S.		-6%	+5%	-7%	+4%	-1%	+3%
SA	N.S.		-4%	+4%	-5%	+3%	+1%	+3%
SAM								
	Summer		Autumn		Winter		Spring	
	Neg.	Pos.	Neg.	Pos.	Neg.	Pos.	Neg.	Pos.
NSW	+2%	-2%	N.S.		N.S.		-2%	+1%
QLD	+2%	0%	N.S.		N.S.		0%	-1%
VIC	N.S.		N.S.		N.S.		N.S.	
SA	+2%	0%	N.S.		N.S.		N.S.	

Table 4 - Results from discrete correlation of climate drivers to ROOFTOP generation.

ENSO								
	Summer		Autumn		Winter		Spring	
	Neg.	Pos.	Neg.	Pos.	Neg.	Pos.	Neg.	Pos.
NSW	-1%	+4%	+1%	+4%	N.S.		-3%	+3%
QLD	-3%	+2%	N.S.		-1%	+1%	-4%	+5%
VIC	N.S.		N.S.		N.S.		-1%	0%
SA	N.S.		N.S.		N.S.		-1%	+1%
DMI								
	Summer		Autumn		Winter		Spring	
	Neg.	Pos.	Neg.	Pos.	Neg.	Pos.	Neg.	Pos.
NSW	N.S.		N.S.		0%	+3%	0%	+5%
QLD	N.S.		+2%	0%	+3%	-1%	+1%	+4%
VIC	N.S.		-6%	+3%	-5%	+3%	3%	2%
SA	N.S.		-4%	+3%	-3%	+4%	2%	0%
SAM								
	Summer		Autumn		Winter		Spring	
	Neg.	Pos.	Neg.	Pos.	Neg.	Pos.	Neg.	Pos.
NSW	+3%	-1%	N.S.		N.S.		1%	0%
QLD	+1%	-1%	N.S.		N.S.		-1%	-2%
VIC	N.S.		N.S.		N.S.		N.S.	
SA	+1%	-1%	N.S.		N.S.		N.S.	

Table 5 - Results from discrete correlation of climate drivers to WIND generation.

ENSO								
	Summer		Autumn		Winter		Spring	
	Neg.	Pos.	Neg.	Pos.	Neg.	Pos.	Neg.	Pos.
NSW	-2.1%	-2.4	N.S.		+2%	-5%	N.S.	
QLD	-2%	0%	N.S.		+2%	0%	N.S.	
VIC	-1%	0%	+2%	-8%	0%	-6%	-5%	-4%
SA	+1%	0%	+2%	-4%	+3%	-5%	-2%	-7%
DMI								
	Summer		Autumn		Winter		Spring	
	Neg.	Pos.	Neg.	Pos.	Neg.	Pos.	Neg.	Pos.
NSW	N.S.		N.S.		N.S.		N.S.	
QLD	N.S.		-3%	+1%	N.S.		N.S.	
VIC	+2%	-3%	-1%	-11%	-1%	-5%	8%	-5%
SA								
SAM								
	Summer		Autumn		Winter		Spring	
	Neg.	Pos.	Neg.	Pos.	Neg.	Pos.	Neg.	Pos.
NSW	N.S.		N.S.		0%	-5%	4%	-3%
QLD	N.S.		N.S.		N.S.		N.S.	
VIC	+5%	-4%	7%	1%	-6%	-3%	+2%	-3%
SA	+3%	-3%	+3%	-1%	-1%	-4%	+2%	-3%

As can be seen from the Tables above, the variations, even if statistically significant, aren't too big. However, it's important to mention the relevance of the number of low outliers in the boxplots of Section 2.4, where certain trends can be observed with more low outliers in one state of the climate drivers.

On the other hand, a trend is observed where VIC and SA coincide in the statistical relevance with the climate drivers, and NSW and QLD also coincide between each other.

3.1.2. Comparison between discrete and continuous analysis

The advantage of looking at continuous correlations is the possibility to use the analysis to create a predictive model or any other type of model, with indicators based in the continuous relationships analysed. However, as can be observed in Section 2.3, most of the trends are coherent with the behaviour of each climate driver but they mostly follow very weak correlations with high deviations in the data.

On the other hand, the advantage of analysing discrete variables is the possibility to classify time periods (such as weeks) depending on their climate driver classification. Additionally, as mentioned above, the low outliers of the boxplots also give useful information. However, as is observed in some cases, insufficient amount of datapoints means the statistical significance is not met, even if there's a clear visual trend

3.1.3. Implications of results

As has been mentioned above, the results obtained in this thesis show certain trends and correlations relating to climate drivers. However, these trends, in most cases, aren't strong and other factors can influence VRE generation much more.

On the other hand, it has been shown that VRE generation in southern states (VIC-SA) and eastern states (NSW-QLD) show similar behaviour between each other towards climate drivers. Most notably, from the Tables shown in Section 3.1.1, we can see how the southern states show lower correlations towards climate drivers, with a considerable number of correlations being statistically insignificant.

3.2. Discussion on the thesis

This thesis has focused on an analysis into the correlations of climate drivers in Australia and VRE generation. The correlation analysis, both continuous and discrete, proved how there are regional differences of climate drivers' effects but also how other factors, not studied in this thesis, might dominate the variability of VRE generation.

On the other hand, this topic, as has been mentioned in the Literature Review, is very relevant and it is being studied more and more. In this sense, further studied could complement this thesis:

- More data spanning longer timeframes or with smaller spatial resolution could be used to further study the regional differences of climate drivers.
- With the continuous analysis, a model to predict VRE generation depending on an upcoming climate driver could be developed. However, other factors would have to be incorporated and studied because, as was mentioned before, climate drivers are not the dominant cause of VRE long-term variability.
- The interaction between climate drivers, and the combination of them could be studied to see if the VRE generation is further affected. For example, when El Niño and a negative SAM occur simultaneously.

Conclusion

The study of long-term variability of VRE generation is essential for future grids with high percentages of RE integration. The reliability of the electrical grid should be guaranteed while not oversizing excessively the capacity of the different energy sources. In order to optimally plan for a future grid, the behaviour of each non-dispatchable energy source towards any factor in the environment should be extensively studied and clearly understood. In that respect this thesis has contributed towards the understanding of the effects climate drivers have on VRE generation in Australia.

Chapter 1, presented each climate driver by providing a definition, explaining how why it occurs and how it changes, reviewing the different methods for calculating it, and showing its effects on the Australian climate. In the second part, a focus was put on the studies conducted in different locations that analysed climate driver effects to VRE production. Finally, taking into account the different literature gaps identified, and with Iberdrola Australia's interests in mind, the research question was outlined

In Chapter 2, the methodology of the analysis together with the results was presented. As mentioned above, the objective of this analysis was to establish the effects climate drivers cause on VRE production in Australia. First of all, each data set was explained and visualised. After that, the methodology of the correlation analysis was presented and, finally, the results were shown in the form of scatter plots and box plots.

Finally, in Chapter 3 a discussion into the results of the analysis and into the thesis objectives and further steps was detailed. Firstly, in the discussion of the results, a quantification of the discrete results was obtained, and the implications were detailed. In the last part of this chapter, a critical analysis of the thesis was made, with possible further steps and gaps identified.

Annex I. Statistical Significance Results

Welchs T-test (2-sample, unpaired) for solar weekly generation:
alpha = 0.05

I. State: NSW

1. NSW-NINO34 t-test:
Summer: Ttest_indResult(statistic=-1.8367061087230114, pvalue=0.06691947622563761), N.S.
Autumn: Ttest_indResult(statistic=-3.051011789148412, pvalue=0.002496548194050179)
Winter: Ttest_indResult(statistic=-3.820428955608726, pvalue=0.0001562247040270109)
Spring: Ttest_indResult(statistic=-6.348491073744461, pvalue=4.716058940173319e-10)

2. NSW-SAM t-test:
Summer: Ttest_indResult(statistic=2.8575469987450153, pvalue=0.004636997994459214)
Autumn: Ttest_indResult(statistic=-1.461300680355736, pvalue=0.1454738312662071), N.S.
Winter: Ttest_indResult(statistic=-0.5819769381133816, pvalue=0.5612786793123605), N.S.
Spring: Ttest_indResult(statistic=2.478937499779576, pvalue=0.013868911353277504)

3. NSW-DMI t-test:
Summer: Ttest_indResult(statistic=0.9508346834167944, pvalue=0.3483492890850933), N.S.
Autumn: Ttest_indResult(statistic=-0.7680491561175923, pvalue=0.4441526183600636), N.S.
Winter: Ttest_indResult(statistic=-5.997868550820508, pvalue=1.105324818510274e-08)
Spring: Ttest_indResult(statistic=-4.724823183431537, pvalue=1.2807901900506723e-05)

II. State: QLD

1. QLD-NINO34 t-test:
Summer: Ttest_indResult(statistic=-3.5179987997988227, pvalue=0.0004785072577394062)
Autumn: Ttest_indResult(statistic=-1.7219386304189082, pvalue=0.08610188365452819), N.S.
Winter: Ttest_indResult(statistic=-3.2079985454637843, pvalue=0.0014534918015745037)
Spring: Ttest_indResult(statistic=-6.599855271889879, pvalue=1.0760142785575213e-10)

2. QLD-SAM t-test:
Summer: Ttest_indResult(statistic=2.672151998993658, pvalue=0.008036551155407728)
Autumn: Ttest_indResult(statistic=-1.4490858586322684, pvalue=0.14889330184882424), N.S.
Winter: Ttest_indResult(statistic=0.27577497377223853, pvalue=0.7830295871399061), N.S.
Spring: Ttest_indResult(statistic=2.963379139817167, pvalue=0.0033549853781595722)

3. QLD-DMI t-test:
Summer: Ttest_indResult(statistic=1.1977193988131818, pvalue=0.23918598088069154), N.S.
Autumn: Ttest_indResult(statistic=1.7287841956210388, pvalue=0.0864793702506977), N.S.
Winter: Ttest_indResult(statistic=-3.0451901058070208, pvalue=0.002630803702110242)
Spring: Ttest_indResult(statistic=-3.3324207237945416, pvalue=0.0015962628426797743)

III. State: VIC

1. VIC-NINO34 t-test:
Summer: Ttest_indResult(statistic=-0.8237315319177387, pvalue=0.4105327644120943), N.S.
Autumn: Ttest_indResult(statistic=-2.1610073345182856, pvalue=0.03160959165661796)
Winter: Ttest_indResult(statistic=-1.503783554410005, pvalue=0.13350039607817596), N.S.
Spring: Ttest_indResult(statistic=-5.5236809750534235, pvalue=5.15637041770487e-08)

2. VIC-SAM t-test:
Summer: Ttest_indResult(statistic=1.7853502941793042, pvalue=0.07542765425801941), N.S.
Autumn: Ttest_indResult(statistic=-0.23638670426062716, pvalue=0.8133618059480455), N.S.
Winter: Ttest_indResult(statistic=-0.6590316451985394, pvalue=0.5106655989004643), N.S.
Spring: Ttest_indResult(statistic=-0.16260599995620711, pvalue=0.8709660743958091), N.S.

3. VIC-DMI t-test:
Summer: Ttest_indResult(statistic=-0.6668816834332513, pvalue=0.5092296661299623), N.S.
Autumn: Ttest_indResult(statistic=-2.793474734209399, pvalue=0.006172249720814905 5)
Winter: Ttest_indResult(statistic=-3.8742294038843923, pvalue=0.00014858269950889565)
Spring: Ttest_indResult(statistic=-5.440358743674139, pvalue=7.907646449844718e-07)

IV. State: SA

1. SA-NINO34 t-test:
Summer: Ttest_indResult(statistic=-1.1004125307545578, pvalue=0.2717317566975444), N.S.
Autumn: Ttest_indResult(statistic=-2.2014647801094442, pvalue=0.02857724841698715)
Winter: Ttest_indResult(statistic=-0.46125627788386897, pvalue=0.6448861207779106), N.S.
Spring: Ttest_indResult(statistic=-5.155080696476691, pvalue=3.571201812492423e-07)

2. SA-SAM t-test:
Summer: Ttest_indResult(statistic=2.2953657069298203, pvalue=0.022584497219114777)
Autumn: Ttest_indResult(statistic=0.7040295032093565, pvalue=0.4821935334220183), N.S.
Winter: Ttest_indResult(statistic=-0.4934957919409934, pvalue=0.622222037055975), N.S.
Spring: Ttest_indResult(statistic=0.4176795913322317, pvalue=0.6765576205988202), N.S.

3. SA-DMI t-test:

Summer: Ttest_indResult(statistic=-2.0012073848479073, pvalue=0.0532543898565955), N.S.
Autumn: Ttest_indResult(statistic=-3.3939394774858886, pvalue=0.0009629671212513831)
Winter: Ttest_indResult(statistic=-4.521878983678702, pvalue=1.119504205106936e-05)
Spring: Ttest_indResult(statistic=-5.178785008680834, pvalue=2.9419180985706524e-06)

Welchs T-test (2-sample, unpaired) for Rooftop weekly generation:
alpha = 0.05

I. State: NSW

1. NSW-NINO34 t-test:
- Summer: Ttest_indResult(statistic=-2.4515723369703872, pvalue=0.014601274931019656)
- Autumn: Ttest_indResult(statistic=-2.5189075161482344, pvalue=0.012335065928235477)
- Winter: Ttest_indResult(statistic=-1.6848846492570524, pvalue=0.0928540670660556), N.S.
- Spring: Ttest_indResult(statistic=-4.120217284270162, pvalue=4.375878589530377e-05)

2. NSW-SAM t-test:
- Summer: Ttest_indResult(statistic=2.731268990860768, pvalue=0.0067635211808527804)
- Autumn: Ttest_indResult(statistic=-1.0217679299920566, pvalue=0.3080770667105938), N.S.
- Winter: Ttest_indResult(statistic=-0.6810951204870122, pvalue=0.4967389509821879), N.S.
- Spring: Ttest_indResult(statistic=2.7291901626731647, pvalue=0.006822378754141602)

3. NSW-DMI t-test:
- Summer: Ttest_indResult(statistic=1.0280740193927618, pvalue=0.31098690196780193), N.S.
- Autumn: Ttest_indResult(statistic=0.12053143431319122, pvalue=0.9043108413024573), N.S.
- Winter: Ttest_indResult(statistic=-3.1215912921450633, pvalue=0.0020980771502492478)
- Spring: Ttest_indResult(statistic=-2.448577770261531, pvalue=0.01599241333314819)

II. State: QLD

1. QLD-NINO34 t-test:
- Summer: Ttest_indResult(statistic=-4.490131184492277, pvalue=9.023742397543045e-06)
- Autumn: Ttest_indResult(statistic=-1.7472916340687583, pvalue=0.08161185364091224), N.S.
- Winter: Ttest_indResult(statistic=-2.570445204981473, pvalue=0.01054789741369844)
- Spring: Ttest_indResult(statistic=-5.835985628240554, pvalue=9.39309006578495e-09)

2. QLD-SAM t-test:
- Summer: Ttest_indResult(statistic=2.996562373804676, pvalue=0.003008582546806431)
- Autumn: Ttest_indResult(statistic=-1.136624811683274, pvalue=0.2570473920749767), N.S.
- Winter: Ttest_indResult(statistic=0.8343493971773053, pvalue=0.40515343284957406), N.S.
- Spring: Ttest_indResult(statistic=3.734443694361249, pvalue=0.0002355927255913336)

3. QLD-DMI t-test:
- Summer: Ttest_indResult(statistic=1.3865393958305394, pvalue=0.17446594077442637), N.S.
- Autumn: Ttest_indResult(statistic=2.421028466171255, pvalue=0.017060784274322515)
- Winter: Ttest_indResult(statistic=-2.2117426411581818, pvalue=0.028086707651677693)
- Spring: Ttest_indResult(statistic=-2.850672597054842, pvalue=0.005941286151869067)

III. State: VIC

1. VIC-NINO34 t-test:
- Summer: Ttest_indResult(statistic=-0.5513881088032596, pvalue=0.5816445678972137), N.S.
- Autumn: Ttest_indResult(statistic=-0.6891672378121804, pvalue=0.491303918885002), N.S.
- Winter: Ttest_indResult(statistic=-1.4365901265271341, pvalue=0.15168415952963843), N.S.
- Spring: Ttest_indResult(statistic=-4.212048181340843, pvalue=2.9620870930370046e-05)

2. VIC-SAM t-test:
- Summer: Ttest_indResult(statistic=1.7733297031905417, pvalue=0.07740156310270035), N.S.
- Autumn: Ttest_indResult(statistic=0.8863640330861874, pvalue=0.37642628998204186), N.S.
- Winter: Ttest_indResult(statistic=-0.8616571688335809, pvalue=0.39003269634985116), N.S.
- Spring: Ttest_indResult(statistic=-0.2062445112606557, pvalue=0.8367755953789487), N.S.

3. VIC-DMI t-test:
- Summer: Ttest_indResult(statistic=-0.6860231104542879, pvalue=0.4977140890252816), N.S.
- Autumn: Ttest_indResult(statistic=-2.193905219984487, pvalue=0.030762657320787454)
- Winter: Ttest_indResult(statistic=-3.361384938438665, pvalue=0.0009456562322906298)
- Spring: Ttest_indResult(statistic=-4.008706526878567, pvalue=0.00015141173167741595)

IV. State: SA

1. SA-NINO34 t-test:
- Summer: Ttest_indResult(statistic=-1.2393905756472499, pvalue=0.2158374428307578), N.S.
- Autumn: Ttest_indResult(statistic=-0.8159285538946365, pvalue=0.4152222664536932), N.S.
- Winter: Ttest_indResult(statistic=0.4431334884723679, pvalue=0.6579300716545651), N.S.
- Spring: Ttest_indResult(statistic=-4.0914953717917, pvalue=4.936795356439609e-05)

2. SA-SAM t-test:
- Summer: Ttest_indResult(statistic=2.857210567199078, pvalue=0.004650009872446068)
- Autumn: Ttest_indResult(statistic=1.0927628311940392, pvalue=0.2757483466600657), N.S.
- Winter: Ttest_indResult(statistic=0.13741807780811216, pvalue=0.8908423502160392), N.S.
- Spring: Ttest_indResult(statistic=-0.9440953985776687, pvalue=0.34607438666525514), N.S.

3. SA-DMI t-test:
- Summer: Ttest_indResult(statistic=-1.5801032088920586, pvalue=0.12334329966839652), N.S.
- Autumn: Ttest_indResult(statistic=-2.794293268473423, pvalue=0.006115161590315782)
- Winter: Ttest_indResult(statistic=-2.4032576100483585, pvalue=0.017264972610169387)
- Spring: Ttest_indResult(statistic=-4.210115585918356, pvalue=8.353271940700097e-05)

Welchs T-test (2-sample, unpaired) for solar weekly generation:
alpha = 0.05

I. State: NSW

1. NSW-NINO34 t-test:
- Summer: Ttest_indResult(statistic=2.8720412638877804, pvalue=0.004267176601101375)
- Autumn: Ttest_indResult(statistic=1.4391435714882919, pvalue=0.15122053866028048), N.S.
- Winter: Ttest_indResult(statistic=2.2421106123576835, pvalue=0.025546179237207076)
- Spring: Ttest_indResult(statistic=0.769941993051984, pvalue=0.44167195590284414), N.S.

2. NSW-SAM t-test:
- Summer: Ttest_indResult(statistic=-0.9782027334351643, pvalue=0.3289276820481887), N.S.
- Autumn: Ttest_indResult(statistic=0.9481652871718216, pvalue=0.34413682103404253), N.S.
- Winter: Ttest_indResult(statistic=3.2644091391989236, pvalue=0.001310754206120435)
- Spring: Ttest_indResult(statistic=2.2902236666582567, pvalue=0.022881158991853254)

3. NSW-DMI t-test:
- Summer: Ttest_indResult(statistic=-0.338900372322163, pvalue=0.7368901221988158), N.S.
- Autumn: Ttest_indResult(statistic=1.3901303841630224, pvalue=0.16808877549216772), N.S.
- Winter: Ttest_indResult(statistic=1.7444717336947004, pvalue=0.08261413928229545), N.S.
- Spring: Ttest_indResult(statistic=0.3362459282329326, pvalue=0.7376639375867153), N.S.

II. State: QLD

1. QLD-NINO34 t-test:
- Summer: Ttest_indResult(statistic=2.320998253849533, pvalue=0.020724703865891897)
- Autumn: Ttest_indResult(statistic=1.0422500805006718, pvalue=0.29815518373999206), N.S.
- Winter: Ttest_indResult(statistic=2.085374989112166, pvalue=0.037720163433748136)
- Spring: Ttest_indResult(statistic=0.9446759042085024, pvalue=0.3452511918065434), N.S.

2. QLD-SAM t-test:
- Summer: Ttest_indResult(statistic=-0.4825045803819577, pvalue=0.6298740526447804), N.S.
- Autumn: Ttest_indResult(statistic=0.5238266741178006, pvalue=0.600954430849777), N.S.
- Winter: Ttest_indResult(statistic=-0.05259758276131489, pvalue=0.958112513278405), N.S.
- Spring: Ttest_indResult(statistic=0.46493949111071103, pvalue=0.6424004982767091), N.S.

3. QLD-DMI t-test:
- Summer: Ttest_indResult(statistic=1.19942914565079, pvalue=0.23842138623426837), N.S.
- Autumn: Ttest_indResult(statistic=-2.226555241877392, pvalue=0.02818721751946971)
- Winter: Ttest_indResult(statistic=1.1404164514184196, pvalue=0.2555510324094307), N.S.
- Spring: Ttest_indResult(statistic=-0.13295085212318425, pvalue=0.8945781015160714), N.S.

III. State: VIC

1. VIC-NINO34 t-test:
- Summer: Ttest_indResult(statistic=2.4869661347670893, pvalue=0.013241280920976664)
- Autumn: Ttest_indResult(statistic=0.011686286586623231, pvalue=0.9906837214363742), N.S.
- Winter: Ttest_indResult(statistic=1.2646435342448459, pvalue=0.20680586361154996), N.S.
- Spring: Ttest_indResult(statistic=1.080357095378395, pvalue=0.2804659289960474), N.S.

2. VIC-SAM t-test:
- Summer: Ttest_indResult(statistic=0.5477131533390565, pvalue=0.5843822209602049), N.S.
- Autumn: Ttest_indResult(statistic=0.5782478647749897, pvalue=0.5637143628233476), N.S.
- Winter: Ttest_indResult(statistic=0.3371257912147255, pvalue=0.7363828385433647), N.S.
- Spring: Ttest_indResult(statistic=1.939726356641563, pvalue=0.05362637877243613), N.S.

3. VIC-DMI t-test:
- Summer: Ttest_indResult(statistic=-0.3737952034536383, pvalue=0.710837136322503), N.S.
- Autumn: Ttest_indResult(statistic=2.6166716430152963, pvalue=0.010487917129823823)
- Winter: Ttest_indResult(statistic=0.03559579326643037, pvalue=0.9716377642175816), N.S.
- Spring: Ttest_indResult(statistic=1.408563510755974, pvalue=0.1632803289467111), N.S.

IV. State: SA

1. SA-NINO34 t-test:
- Summer: Ttest_indResult(statistic=3.1780561825375444, pvalue=0.0015838549451396716)
- Autumn: Ttest_indResult(statistic=0.838352810163019, pvalue=0.4025394180645835), N.S.
- Winter: Ttest_indResult(statistic=1.27040178205473, pvalue=0.204739822979796), N.S.
- Spring: Ttest_indResult(statistic=1.3243852995315013, pvalue=0.18594553784254517), N.S.

2. SA-SAM t-test:
- Summer: Ttest_indResult(statistic=0.38336058622286334, pvalue=0.7017813641690733), N.S.
- Autumn: Ttest_indResult(statistic=1.38716257980734, pvalue=0.16684735961057168), N.S.
- Winter: Ttest_indResult(statistic=1.008796701697709, pvalue=0.3143179817393549), N.S.
- Spring: Ttest_indResult(statistic=2.0812128985955107, pvalue=0.038504144938917614)

3. SA-DMI t-test:
- Summer: Ttest_indResult(statistic=0.47878521410477975, pvalue=0.6351115349366783), N.S.
- Autumn: Ttest_indResult(statistic=1.9911491089592555, pvalue=0.049792356105957496)
- Winter: Ttest_indResult(statistic=1.0549406736549618, pvalue=0.2926389937557417), N.S.
- Spring: Ttest_indResult(statistic=1.5420081269638966, pvalue=0.1275135290722739), N.S.

Bibliography

[1] International Energy Agency, “Net Zero by 2050,” 2021.

[2] AEMO, “The National Electricity Market Fact Sheet,” 2021.

[3] Australian Energy Regulator (AER), “State of the energy market 2023,” 2023.

[4] AEMO, “Diagrams and previous maps,” 2023. [Online]. Available: https://aemo.com.au/energy-systems/electricity/national-electricity-market-nem/nem-forecasting-and-planning/forecasting-and-planning-data/diagrams-and-previous-maps.

[5] The Australia Institute, “Largest coal plant to close early, but where is the national roadmap to manage the rest?,” February 2022. [Online]. Available: https://australiainstitute.org.au/post/largest-coal-plant-to-close-early-but-where-is-the-national-roadmap-to-manage-the-rest/.

[6] AEMO, “2022 Integrated System Plan,” 2022.

[7] Australian Government, “Australian Government Climate Change commitments, policies and programs,” 2022. [Online]. Available: https://www.aofm.gov.au/sites/default/files/2022-11-28/Aust%20Govt%20CC%20Actions%20Update%20November%202022_1.pdf.

[8] Energy Matters, “Is Australia on Track to Meet Its 2030 Renewable Energy Target?,” October 2023. [Online]. Available: https://www.energymatters.com.au/renewable-news/is-australia-on-track-to-meet-its-2030-renewable-energy-target/.

[9] Iberdrola Australia, “Our Assets,” [Online]. Available: https://www.iberdrola.com.au/our-assets/asset-map/.

[10] Climate.gov, “El Niño & La Niña (El Niño-Southern Oscillation),” 2023. [Online]. Available: https://www.climate.gov/enso.

[11] National Oceanic and Atmospheric Administration (NOAA), "Understanding El Niño," 2016. [Online]. Available: https://www.noaa.gov/understanding-el-nino.

[12] C. Wang, C. Deser, J.-Y. Yu, P. DiNezio and A. Clement, “El Niño and Southern Oscillation (ENSO): A Review,” *Coral Reefs of the Eastern Tropical Pacific,* pp. 85-106, 2016.

[13] Physical Sciences Laboratory, NOAA, “El Niño Southern Oscillation (ENSO),” [Online]. Available: https://psl.noaa.gov/enso/.

[14] Met Office, “El Niño, La Niña and the Southern Oscillation,” 2014. [Online]. Available: https://www.metoffice.gov.uk/research/climate/seasonal-to-decadal/gpc-outlooks/el-nino-la-nina/enso-description.

[15] National Oceanic and Atmospheric Administration (NOAA), “Southern Oscillation Index (SOI),” 2023. [Online]. Available: https://www.ncei.noaa.gov/access/monitoring/enso/soi.

[16] W. K and T. MS, “Monitoring ENSO in COADS with a seasonally adjusted principal component index.,” in *Climate Diagnostics Workshop*, Oklahoma, 1993.

[17] S. Mourtzinis, B. V. Ortiz and D. Damianidis, “Climate Change and ENSO Effects on Southeastern US Climate Patterns and Maize Yield,” *Scientific Reports,* vol. 6, 2016.

[18] A. Mahmood, T. M. A. Khan and N. Faisal, "Correlation between multivariate enso index (mei) and pakistan's summer rainfall," *Pakistan Journal of Meteorology,* vol. 1, no. 2, 2004.

[19] A. Lv, L. Fan and W. Zhang, "Impact of ENSO Events on Droughts in China," *Atmosphere,* vol. 13, 2022.

[20] Physical Sciences Laboratory, NOAA, "Multivariate ENSO Index Version 2 (MEI.v2)," [Online]. Available: https://psl.noaa.gov/enso/mei/.

[21] Bureau of Meteorology (BOM), "ENSO Outlook," 2023. [Online]. Available: http://www.bom.gov.au/climate/enso/outlook/.

[22] Bureau of Meteorology (BOM), "El Niño," [Online]. Available: http://www.bom.gov.au/climate/about/australian-climate-influences.shtml?bookmark=elnino.

[23] Bureau of Meteorology (BOM), "What is El Niño and how does it impact Australia?," 2021. [Online]. Available: http://www.bom.gov.au/climate/updates/articles/a008-el-nino-and-australia.shtml.

[24] W. Cai and T. Cowan, "La Niña Modoki impacts Australia autumn rainfall variability," *Geophysical Research Letters,* vol. 36, no. 12, 2009.

[25] E. Lim, D. Hudson and M. Wheeler, "Why Australia was not wet during spring 2020 despite La Niña," *Scientific Reports,* vol. 11, 2021.

[26] N. H. Saji, B. N. Goswami, P. N. Vinayachandran and T. Yamagata, "A dipole mode in the tropical Indian Ocean," *Nature,* vol. 401, no. 6751, pp. 360-363, 1999.

[27] Bureau of Meteorology (BOM), "Climate Monitoring Graphs," 2023. [Online]. Available: http://www.bom.gov.au/climate/enso/indices.shtml?bookmark=iod.

[28] P. Vinayachandran, F. Pavanathara and S. Rao, "Indian Ocean dipole: processes and impacts," *Current Trends in Science,* 2010.

[29] Bureau of Meteorology (BOM), "Indian Ocean," [Online]. Available: http://www.bom.gov.au/climate/about/australian-climate-influences.shtml?bookmark=iod.

[30] B. Davies, "Southern Annular Mode," 2023. [Online]. Available: https://www.antarcticglaciers.org/glaciers-and-climate/southern-annular-mode/.

[31] G. J. Marshall, "Trends in the Southern Annular Mode from Observations and Reanalyses," *Journal of Climate,* vol. 16, no. 24, p. 4134–4143, 2003.

[32] D. Y. Lee, M. R. Petersen and W. Lin, "The Southern Annular Mode and Southern Ocean Surface Westerly Winds in E3SM," *Earth and Space Science,* vol. 6, no. 12, pp. 2624-2643, 2019.

[33] IPCC, "AR4 Climate Change 2007: The Physical Science Basis," 2007.

[34] British Antarctic Survey, "An observation-based Southern Hemisphere Annular Mode Index," 2023. [Online]. Available: http://www.nerc-bas.ac.uk/icd/gjma/sam.html.

[35] M. Ho, A. S. Kiem and D. C. Verdon-Kidd, "The Southern Annular Mode: a comparison of indices," *Hydrology and Earth System Sciences,* vol. 16, no. 3, 2012.

[36] Bureau of Meteorology (BOM), "Southern Annular Mode," 2023. [Online]. Available: http://www.bom.gov.au/watl/about-weather-and-climate/australian-climate-influences.shtml?bookmark=sam.

[37] K. Mohammadi and N. Goudarzi, "Study of inter-correlations of solar radiation, wind speed and precipitation under the influence of El Niño Southern Oscillation (ENSO) in California," *Renewable Energy,* vol. 120, 2018.

[38] D. Richardson, A. J. Pitman and N. N. Ridder, “Climate influence on compound solar and wind droughts in Australia,” *Climate and Atmospheric Science volume,* vol. 6, 2023.

[39] F. Henao, J. P. Viteri, Y. Rodríguez, J. Gómez and I. Dyner, “Annual and interannual complementarities of renewable energy sources in Colombia,” *Renewable and Sustainable Energy Reviews,* vol. 134, 2020.

[40] Y. Wei, J. Zhang, Y. Chen and Y. Wang, “The impacts of El Niño-southern oscillation on renewable energy stock markets: Evidence from quantile perspective,” *Energy,* vol. 260, 2022.

[41] J. Restrepo-Trujillo, R. Moreno-Chuquen, F. Jiménez-García, W. Flores and H. Chamorro, “Scenario Analysis of an Electric Power System in Colombia Considering the El Niño Phenomenon and the Inclusion of Renewable Energies,” *Energies,* vol. 15, 2022.

[42] J. Jurasz, F. Canales, A. Kies, M. Guezgouz and A. Beluco, “A review on the complementarity of renewable energy sources: Concept, metrics, application and future research directions,” *Solar Energy,* vol. 195, 2020.

[43] NOAA, “MEI Index,” 2018. [Online]. Available: https://psl.noaa.gov/enso/mei.old/table.html.

[44] A. Mahmood, T. M. A. Khan and N. Faisal, “Correlation between multivariate enso index (mei) and pakistan’s summer rainfall,” *Pakistan Journal of Meteorology,* 2004.