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**The Wind Energy Potential of South Africa's Eastern
Cape Province in a Changing Climate**

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Degree of Doctor of Philosophy:

A thesis submitted to the Faculty of Science, University of the Witwatersrand,
Johannesburg, in fulfilment of the requirements for the degree of Doctor of
Philosophy.

16 October 2024, Johannesburg

Declaration

I declare that this Thesis is my own, unaided work. It is being submitted for the Degree of Doctor of Philosophy at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at any other University.

A handwritten signature in black ink, appearing to read 'Gregory Brent Landwehr', written in a cursive style. The signature is positioned above a horizontal line.

Gregory Brent Landwehr

16 October 2024 at Somerset West.

Abstract

Due to the abundance of wind and solar renewable energy resources across South Africa, and the comparative low cost of installation and operation of wind and solar energy infrastructure, it is inevitable that the country's dependence on fossil fuels for energy will decline in the future. At a practical level, developing wind energy facilities entails a complex array of activities and the ~20-30 year life spans of such facilities intrinsically implies that they will experience climate change. However, insufficient research and related modelling have been undertaken in South Africa to quantify future variability and systematic changes in the wind resource as it relates to specific synoptic weather types and wind energy production

The aim of this thesis is to develop methodologies to understand the synoptic drivers of regional wind energy production potential and in turn assess how and why South Africa's wind energy production potential may change as a function of changing circulation patterns in a changing climate.

The wind energy potential of the Eastern Cape Province of South Africa is quantified using energy yield analysis techniques. These results are mapped onto commonly occurring synoptic types for the region to assign an energy potential to each. When the changing frequency of these synoptic weather types is calculated in a climate change impacted future using Global Climate Models, it is possible to quantify the change in wind energy potential in the long term. Results show that the synoptic-circulation pattern with the highest wind energy potential is the Atlantic Ocean ridging High with its centre at about 30 °S, behind a northward displaced mid-latitude cyclone. Global Climate Model projections of the frequency occurrence of these high energy synoptic states show a decrease in frequency at all global warming temperature thresholds and in turn a decrease in wind energy production. The likely cause of this being the poleward expansion of the descending limb of the Hadley circulation which shifts these synoptic systems southwards.

The methodologies presented in this thesis provide South Africa with the necessary climate change risk assessment and mitigation capability to address these impacts on the wind energy sector in South Africa.

Acknowledgements

This work is dedicated to all my family, friends, and colleagues, who have given me the strength and the will to successfully complete it. Credit should go to my long-suffering wife Bronwyn, and children Beth, Ben and Dan for their unmatched patience and support during this time.

A special thank you must go to my supervisors, Prof. Francois Engelbrecht who supported and guided this research from the start and to Chris Lennard for his valuable contributions during the process.

Finally, it is important to note that this work was funded by the National Research Foundation of South Africa through its Earth System Science Research Programme, Grant 118598.

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List of Abbreviations

°C	Degrees Celsius
AEP	Annual Energy Production
AGL	Above ground level
AMJ	April May June
AR6	IPCC Sixth Assessment Report
BMU	Best Matching Unit
BOP	Balance of Plant
BW	Bid Window
CanESM5	The Canadian Earth System Model version 5
CDO	Climate Data Operators
CF	Capacity factor (Net or Gross)
CFD	Computational Fluid Dynamics
CMIP6	Coupled Model of Intercomparison Project version 6
COP26	26th Conference of Parties
CORDEX	COordinated Regional climate Downscaling EXperiment
CPS	Current Policies Scenario
CPU	Central Processing Unit
CSAG	Climate System Analysis Group
CSIR	Council for Scientific and Industrial Research
CSP	Concentrated Solar Power
DMRE	The Department of Mineral Resources and Energy
DNV	Det Norske Veritas
DTM	Digital Terrain Model

EAF	Energy Availability Factor
EC	Eastern Cape
EC-Earth3	European Consortium Earth system model
ECMWF	European Centre for Medium-Range Weather Forecasts
ED	Euclidean Distance
ERA5	Fifth generation ECMWF atmospheric reanalysis of the global climate
EU	European Union
EYA	Energy Yield Analysis
FIT	Feed-in-tariff
GB	Gigabyte
GCCA	Generation Connection Capacity Assessment of the 2024 Transmission Network
GCI	Global Change Institute
GCM	Global Climate Model
GPH	Geopotential Height
GUI	Graphical User Interface
GW	Gigawatt
GWh	Gigawatt Hour
hPa	Hectopascal
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronic Engineers
IGCAR	Interim Grid Capacity Allocation Rules
IPCC	Intergovernmental Panel on Climate Change

IPG	international Partners Group
IPP	Independent Power Producer
IRP	Integrated Resource Plan
ITCZ	Inter-Tropical Convergence Zone
JAS	July August September
JET	Just Energy Transition
JFM	January February March
kW	Kilowatt
kWh	Kilowatt Hour
MAE	Mean Absolute Error
MERRA2	Modern-Era Retrospective Analysis for Research and Applications, Version 2
MPI-ESM	Max Planck Institute Earth System Model
MTCE	Million Tons Coal Equivalent
MTOE	Million Tons Oil Equivalent
MTS	Main transmission substations
MW	Megawatt
MWh	Megawatt Hour
NCC	NorESM Climate modelling Consortium
NCF	Net Capacity Factor
NDP	National Development Plan
netCDF	Network Common Data Form file format
NorESM2	Norwegian Earth System Model version 2
NREL	National Renewable Energy Lab

OCGT	Open Cycle Gas Turbines
OEM	Original Equipment Manufacturer
OND	October November December
PJ	Petajoule
PPA	Power Purchase Agreement
PV	Photovoltaic
PW	Petawatt Hour
PWh	Petawatt Hour
RAM	Random Access Memory
RE	Renewable Energy
REDZ	Renewable Energy Development Zones
REIPPPP	Renewable Energy Independent Power Producer Procurement programme
RMSE	Root Mean Squared Error
RSA	Republic of South Africa
SAPVIA	South African Photovoltaic Industry Association
SAWEA	South African Wind Energy Association
SBO	Single Buyer Office
SD	Standard deviation
SOCCESM	The Earth System Modelling of the Southern Ocean in a Changing Climate Project
SOM	Self Organising Map
SOMPAK ©	Self Organising Map Program Package
SSP	Shared Socio-economic Pathways

TDP	Transmission Development Plan
TMY	Typical Meteorological Year
TW	Terawatt
TWh	Terawatt Hour
TX	Transmission (overhead powerlines greater than 132 kV)
USD	United States Dollar
V	Volt
VA	Volt Ampere
VRE	Variable Renewable Energy
WASA	Wind Atlas of South Africa
WAsP	Wind Atlas Analysis and Application Program
WEF	Wind Energy Facility
WEMC	World Energy Meteorology Council
WP	Work Package
WRG	Wind Resource Grid
WTG	Wind turbine generator
ZAR	South African Rand

List of Units and Relevant Formulae

1. Electricity

Volt (V): Measure of potential difference

Ampere (A): Measure of current

Ohm (Ω): Measure of resistance

2. Power

1 Watt = 1 Joule/Second: Unit of Power (Rate of Energy Consumption)

Kilowatt (kW): 1 kW = 1000 W

Megawatt (MW): 1 MW = 1000 kW

Gigawatt (GW): 1GW = 1000 MW

Petawatt (PW): 1 PW = 1000 000 GW

Volt Ampere (VA): Unit of Apparent Power

3. Energy

Kilowatt Hour (kWh): Unit of Energy Consumption

Megawatt Hour (MWh): 1MWh = 1000 kWh

Gigawatt Hour (GWh): 1GWh = 1000 MWh

Terawatt Hour (TWh): 1TWh = 1000 GWh = 3.6 PJ

Petawatt Hour (PWh): 1PWh = 1000 TWh

Petajoule (PJ): The Joule is the basic unit of Energy 1PJ = 10¹⁵ Joules

Million Tons Oil Equivalent (MTOE): the amount of energy released by burning one ton of crude oil

Million Tons Coal Equivalent (MTCE): the amount of energy released by burning one ton of crude oil

4. Atmospheric:

Hectopascal (hPa): Unit of Pressure

Geopotential Height (m): Vertical measurement from mean sea level of one unit of mass through one unit of distance in which the gravitational acceleration is constant at 9.81 m/s².

5. Net Capacity Factor:

The ratio of the actual annual net energy yield to the theoretically possible annual energy yield if the plant ran at full capacity all year around. It is used to compare the performance of wind energy facilities. The net capacity factor is different to the capacity factor, the latter implying the ratio of the gross energy yield excluding all losses to the theoretically possible annual energy yield.

$$NCF = \frac{\text{Actual Energy Generated less all losses (MWh)}}{(\text{Plant Capacity (MW)} \times \text{Time Period (h)})} \quad \dots(1)$$

Where: Annual Energy Production: actual annual gross energy
production less losses

6. Statistics:

Root mean square error

The accuracy of energy production predictions is assessed by comparing forecast results with actual energy production at varying timescales. Furthermore, to quantitatively assess the average forecast error the root mean square error (RMSE) is used.

$$\text{Root Mean Square Error (RMSE): } \sqrt{\frac{1}{N} \times \sum_{i=1}^N \epsilon_i^2} \quad \dots(2)$$

Where: N = the number of readings analysed

ϵ_i = Predicted value – Measured value

Standard deviation

The method used to also determine the change in internal rate of return is standard deviation of error.

$$\text{Standard Deviation (STDE)}: \sqrt{\frac{1}{N} \times \sum_{i=1}^N (\epsilon_i - \bar{\epsilon}_i)^2} \quad \dots(3)$$

Where: N = the number of readings analysed

ϵ_i = Predicted value – Measured value

Pearson Correlation between Calculated and Actual Power Comparison

To effectively compare the ERA5 timeseries to the trained self-organising map results, the Pearson correlation coefficient (r) was used and the formula is given below. A correlation coefficient of 1 is the perfect correlation case thus anything close to 1 is desirable.

$$r = \frac{\sum_{i=1}^n (X_i - \bar{X}) \times \sum_{i=1}^n (Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^n (X_i - \bar{X})^2} \times \sqrt{\sum_{i=1}^n (Y_i - \bar{Y})^2}} \quad \dots(4)$$

Where: X, Y = first and second variables to be correlated

Mean Absolute Error

Is a measure of the difference between two similar datasets. In the case of this study, it is the absolute difference between the predicted wind energy production and the actual wind energy production from a WEF.

$$MAE = \frac{\sum_{i=1}^n |Y_i - X_i|}{n} \quad \dots(5)$$

Where: X, Y = first and second variables being compared

n = number of observations being compared

Sens slope and Mann-Kendall (M-K) test

The changes in wind energy production over a 70 year period are analysed with

Sen's slope test (Sen, 1968) and M-K test (Kendall, 1948, Mann, 1945) to determine the statistical significance of the timeseries. The S statistic is the difference between the number of positive and negative differences which occur in the sample dataset.

$$S \text{ statistic} = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sign}(x_i - x_j) \quad \dots(6)$$

Where: n = the number of wind energy yield values

$x_{i,j}$ = wind energy yield value and subsequent value

$\text{sign}(x_i - x_j) = +1$ if $x_j > x_i$ and -1 if $x_j < x_i$

The variance of S is calculated and used to determine the Z statistic which tests the null hypothesis that there is no trend (Kendall, 1948, Mann, 1945).

$$\text{Variance of } S \text{ or } \text{Var}(S) = \frac{n \times (n-1) \times (2n+5)}{18} \quad \dots(7)$$

Where: n = the number of wind energy yield values

For $Z < 0$:

$$Z \text{ statistic} = \frac{S+1}{\sqrt{\text{Var}(S)}} \quad \dots(8)$$

For each pair of y (years) and x (energy) values, the slope is calculated, and the median is used to determine the overall trend in the data (Sen, 1968).

$$\text{Sens Slope} = \frac{y_j - y_i}{x_j - x_i} \quad \dots(9)$$

Where: $y_{i,j}$ = wind energy yield year and subsequent year

$x_{i,j}$ = wind energy yield value and subsequent value

7. Wind Shear

To extrapolate wind speed measurements to the hub height of the wind turbine generators, a wind profile power law is used.

$$u(z) = u(z_1) \times \left(\frac{z}{z_1}\right)^\alpha \quad \dots(10)$$

Where: $u = \text{wind speed } \left(\frac{m}{s}\right)$

$Z = \text{height at which wind speed is calculated (m)}$

$Z_1 = \text{height of reference wind speed (m)}$

$\alpha = \text{wind power profile exponent}$

8. Weibull Distribution per site

To be able to evaluate the potential power output of a wind farm site properly, an accepted method for comparison must be conducted. For this purpose, the Weibull distribution has been used. The A (scale) parameter is used as a measure of the characteristic wind speed of the distribution and signifies generally how windy the position is i.e. a higher value signifies a very windy position and vice versa. The k (shape) parameter takes a value between 1 and 3 with smaller values signifying variable wind speeds and higher values signifying more constant wind speeds. The energy that is contained in the wind can then be expressed using this frequency distribution function. The formula for the Weibull distribution is shown below:

$$f(u) = \frac{k}{A} \times \left(\frac{u}{A}\right)^{k-1} \times e^{-\left(\frac{u}{A}\right)^k} \quad \dots(11)$$

Where: $u = \text{wind speed } \left(\frac{m}{s}\right)$

$A = \text{scale parameter } \left(\frac{m}{s}\right)$

$k = \text{shape parameter}$

9. Euclidean distance

Euclidean distance is the length of the line segment between two points calculated from the Cartesian coordinates of the points using the Pythagorean theorem and is used in the self-organising map to develop a trained result.

$$d(p, q) = \sqrt{\sum_{i=1}^n (q_i - p_i)^2} \quad \dots(12)$$

Where: p, q = two points in Euclidean n – space

q_i, p_i = Euclidean vectors, starting from the
origin of the space (initial point)

n = n – space

10. Wind Power Conversion

The wind power conversion formula calculates the electrical power generated by a wind turbine based on parameters such as wind speed, air density, and the turbines characteristics. It expresses the relationship between these variables to determine the potential output of wind energy and is inherently used within the wind energy modelling software.

$$P = 0.5 \times \rho \times A \times V^3 \times C_p \quad \dots(13)$$

Where: P = Power (in watts)

ρ = Air density (in kg/m^3)

A = Swept area of the turbine blades (in m^2)

V = Wind speed (in m/s)

C_p = Coefficient of performance (dimensionless)

1. CHAPTER 1: Introduction

1.1 Background

Renewable energy installations are growing globally and locally in South Africa because of climate change (BP Energy, 2021). As a corollary to this, high carbon fuel installations are slowing with uncertainty over their future (BP Energy, 2021).

As the background for achieving the objectives this thesis, the following provides a view on the global energy future and a localised outline of South Africa's energy sector growth. This is expanded in relation to the renewable energy sector and the role of weather and climate change in wind energy production.

1.1.1 Global energy future

The International Energy Agencies World Energy Outlook reports for 2018 (IEA, 2018), 2020 (IEA, 2020) and 2023 (IEA, 2023) provide a set of scenarios that explore different possible energy futures. The most conservative scenario namely, the Current Policies Scenario (CPS) indicates what will happen if the world continues along its present path without any changes to existing policy (IEA, 2018). This scenario brings with it a rise in energy demand by 1.3 % per year until 2040 which will result in an unrelenting upward trajectory in energy-related emissions (IEA, 2018). By the late twentieth century, the total global primary energy supply was at around 8 700 million tonnes of oil equivalent (Mtoe) (IEA, 2018). By 2018 that had risen to around 13 800 Mtoe (IEA, 2020). The percentage coming from coal is currently at 25%, oil at 32% and natural gas at 23%. Wind and Solar energy only made up 2% of the total. It is clear however that renewables are growing in their contribution (IEA, 2023). The 2018 report shows a positive outlook for renewables rollout with a shift in energy demand to the developing economies but still shows a projected demand and emissions increase (IEA, 2018).

The 2020 report corroborates the decline in global energy demand and emissions in the BP Energy report, 2021 and shows low impact of COVID on renewable energy installations (IEA, 2020). The opposite is stated for high carbon energy

installations with uncertainty growing about the rebound in their investment (IEA, 2020).

The 2022 report describes an unsettled global energy market with investment in clean energy rising by 40% since 2020 (IEA, 2023). Fossil fuels are foreseen to peak in global demand prior to 2030 with the share edging downwards to 2030 (IEA, 2023). This reiterates global drive towards renewable energy installation is growing in momentum.

1.1.2 History of the energy mix in South Africa

Carbon emissions dominate South Africa's electricity supply system making it one of the worst emitters globally (Ainger, 2022). The path to transition this to renewable energy has been long and dates back to the South African Government's White Paper on Energy Policy (RSA DoME, 1998), published in 1998 after which momentum grown via other mechanisms. This White Paper was written to clarify government policy regarding the supply and consumption of energy until 2008. The policy proposes strengthening existing energy systems and demonstrates a resolve to bring about extensive change in several areas, in particular securing supply through a diversity of primary energy carriers of which renewables makes up a significant part (RSA DoME, 1998).

In 2003, the White Paper on Renewable Energy, (RSA DoME, 2003b), was written to accompany the White Paper on Energy Policy and recognises that the medium and long-term potential of renewable energy is significant. This Paper sets out the South African Government's vision, policy principles, strategic goals and objectives for promoting and implementing renewable energy in South Africa (RSA DoME, 2003b).

Based on these documents, the South African Integrated Resource Plans (IRP) 2003, (RSA DoME, 2003a) and 2019, (RSA Government, 2019), and National Development Plan (NDP), (RSA Government, 2022), were then developed. The former to lay out the proposed generation new build fleet of power generation stations for South Africa for the period 2021 to 2030 with a strong focus on adding renewable energy to the mix during this time. The latter considers social

equity in terms of access to energy and environmental sustainability through reduced emissions.

As further response to the IRP 2019, the Eskom Transmission Development Plan (Eskom, 2023b) outlines the plans for rollout of new energy transmission infrastructure across South Africa for the next ten years mainly to facilitate the introduction of renewable energy generation plants. This document also informs the outlook for renewables amongst other energy resources and with the progress towards an independent National Transmission Company of South Africa in 2024, this will be a key document in the future of wind energy in South Africa (Eskom, 2023b).

Tying all these together is the Generation Connection Capacity Assessment of the 2022 Transmission Network (GCCA, 2022), (Eskom, 2015), which provides stakeholders with an indication of the current and available power capacity for the connection of new generation at the main transmission system (MTS) substations on the Eskom transmission network that may be in service by 2022.

1.1.3 Current and future state of the energy sector in South Africa

In 2017, the Council for Scientific and Industrial Research (CSIR) in South Africa presented in parliament to highlight the South African electricity crises and how solutions must be implemented to address this crisis during the next decade (Bischof-Niemz, 2017). The presentation clearly stated how wind energy will play its part in the energy transition (Bischof-Niemz, 2017). This is corroborated by a follow up study by the CSIR in 2016 (Bofinger et al., 2016) which aimed to drive the renewable energy of South Africa forward and improve the understanding of whether wind and solar resources can be combined in specific spatial areas throughout South Africa. Quantifying how much combined generation from wind and solar energy could be achieved in discrete spatial areas is the major outcome of the study and is widely considered a key contributor to expediting the transition to renewable energy (Bofinger et al., 2016).

Confirmation of current installations of renewable energy in South Africa is provided by the CSIR in a bi-annual report (CSIR, 2020, 2022b) since 2019 listing the Statistics of utility-scale solar PV, wind and CSP in South Africa. At present, renewable energy installations, via the Department of Energy's Renewable Independent Power Producer Programme, amount to approximately ~6.3 GW out of a total power generation capacity of 52.8 GW. Wright et al., (2020), show that the electricity generation capacity of South Africa could rise to 109 GW by 2050 with 33 % (capacity and electricity production) of that coming from wind alone.

1.1.4 Role of weather and climate change in wind energy production

Wind energy production is variable in nature diurnally, seasonally and inter annually (Bofinger, S. et al., 2016). It relies heavily on large synoptic systems to provide the resource needed for WEFs to generate their energy (Van Aarde et al., 2023). As a result, there is an intrinsic dependence of the wind industry on the weather systems impacting it at a synoptic scale (Van Aarde et al., 2023). Furthermore, these synoptic weather patterns are being impacted by climate change and may become more or less frequent over the longer term (Engelbrecht et al., 2014). It is for this reason that an understanding must be developed for how the frequency of these synoptic weather systems will change over time in a temporal and spatial dimensions for the management of future energy systems with high wind penetration.

1.2 Research Rationale

The dependence of South Africa and the global community on conventional types of energy will inevitably reduce in the future due to the abundance of alternative energy resources such as solar and wind with their now overwhelmingly low cost of installation (IPPO, 2022, CSIR, 2020). As a percentage of the total global energy supply, wind energy facilities (WEFs) could provide 10% of the total global energy supply by 2050 (IEA World Energy Outlook, 2023).

South Africa's transition to renewable and sustainable energy system, is a possibility if steps are taken to achieve this (RSA Government, 2019). Moving from coal reliance to a system based on renewable energy is being prompted further by the growing concern over high levels of air pollution in the areas where fossil fuel power plants exist, and the increasing threat of climate change (RSA Government, 2019).

The Eastern Cape (EC) province exhibits an exceptional wind resource potential which can be exploited towards expediting a transition to renewable energy. The variable nature of renewable energy warrants the tools to be able to predict it well and in turn future proof renewable energy generation plants in a changing climate by identifying future risks and designing mitigation measures. These tools don't exist at present in South Africa.

1.3 Aim of the research

South Africa has experienced some significant headwinds in its attempt to simply provide enough energy to its citizens (Creamer, 2012). The stunting of the public renewable energy procurement process in 2022 where no wind energy Power Purchase Agreements (PPAs) out of twenty-three bids were awarded due to lack of grid capacity, has pushed the market more towards private offtakers who have effectively locked up the grid capacity and thus sterilised many well-developed

wind and solar projects (Eskom, 2015). With the advent of a curtailment framework, grid queueing rules instituted by the national utility, Eskom, and most recently, the creation of the National Transmission Company of South Africa, this bottle neck is poised to be released with an influx of variable renewable energy being brought onto the grid in the next decade (Eskom, 2022). It has thus never been more important to understand the long-term variability of the wind resource in South Africa as it relates to Climate Change.

The aim of this research is to assess how a changing climate may impact the wind energy production potential in South Africa and develop a methodology to accomplish this at scale and over the long-term. This will facilitate the early assessment of future risks and thus implementation of mitigation measures to hamper their impact.

1.4 Objectives of the research

This research has the following specific objectives:

1. To quantify the present-day wind climatology, associated net capacity factors of WEFs in South Africa's Eastern Cape Province and related high wind energy producing synoptic weather types using observed data sets and detailed regional climate modelling.
2. To develop a universally applicable methodology for producing detailed projections of how the wind energy production in the Eastern Cape (easily applied to any spatial area) will alter over time under different mitigation scenarios in a changing climate.
3. As a result of 1 and 2, identify contexts within the South African wind industry that will be impacted with the aim of facilitating the future establishment of adaptation and risk mitigation measures for addressing climate change impacts on the renewable energy sector in South Africa.

1.5 Novelty

Quantifying the wind resource in South Africa has, to date, been conducted using measured wind speed and wind direction data from the Wind Atlas of South Africa (WASA) (CSIR, 2019) and in some cases the South Africa Weather Service (SAWS). Thus, the use of detailed regional climate modelling to describe the wind resource in South Africa has been limited to the historical period, to aid in obtaining a spatial description of wind patterns (CSIR, 2019).

The relationship between wind energy production potential and the occurrence of specific synoptic weather types over South Africa has not yet been quantified. Moreover, no research and related modelling have been undertaken in quantifying the future variability and systematic changes in wind energy production in temporal and spatial dimensions, within the context of a changing climate. Obtaining such a quantification is valuable in understanding how and why South Africa's wind energy production potential may change as a function of changing circulation patterns in a changing climate.

This thesis provides a methodology to achieve this outcome within the context of three publications submitted to international journals. The first of these publications has been peer reviewed and was published by the Journal of Theoretical and Applied Climatology in January 2024.

1.6 Structure of thesis

This thesis is divided into 7 chapters and is the form of a publication-based submission.

Chapter 1, the Introduction, outlines the research rationale and then sets out to describe the scope of the thesis by defining its aims, and objectives.

Chapter 2, the Literature review, is arranged in four overarching themes synthesising the relevant literature for each. It identifies the outstanding questions in the existing research that this thesis is trying to answer with the thesis objectives.

Chapter 3, the Spatial area of interest, motivates the selection of the study site and gives a high-level background of the climatology of the Eastern Cape pertaining to wind and a brief statistical justification. A brief synopsis of the energy needs of the province is also given.

Chapter 4, the Methodology, delivers a flow chart summarising the practical steps taken to carry out this research. Further discussion is provided for each step of the methodology.

Chapter 5, Paper 1 (Wind Energy potential of weather systems affecting South Africa's Eastern Cape Province) sets out to firstly provide a brief outline of the national power system of South Africa and then moves into quantifying the wind energy production of the Eastern Cape Province by modelling four potential wind energy facilities. Finally, synoptic weather types affecting wind energy facilities in South Africa are identified and investigated in terms of their wind potential by using self-organising maps (SOMs).

Chapter 6, Paper 2, (Projected changes in the wind energy potential of South Africa's Eastern Cape Province under climate change) provides projections of future changes in wind resource availability under various climate change mitigation scenarios, using the simulations of nine different CMIP6 Global Climate Models (GCMs). A high-level investigation is then presented on the possible commercial impact of the results.

Chapter 7, Paper 3, (Securing the Wind Energy Future of South Africa's Eastern Cape Province by Assessing and Mitigating Climate Change Risk) reviews the

detailed projections of changes in wind potential provided in Chapter 6 and shows the importance of long-term wind energy projections for South Africa's changing climate by identifying areas which may be at risk. Mitigation measures are proposed and practical ways that the methods developed in this thesis can be physically embodied are discussed.

Chapter 8, the Discussion, brings together the three papers (Chapter 5, 6 and 7), and positions them within the existing research. Limitations of the research are also discussed.

Chapter 9, the Conclusion, provides a brief summary of the work presented in the thesis including future work and ways to practical implement it.

2. CHAPTER 2: Literature Review

2.1 Introduction

The scope of this literature survey covers publications pertinent to the objectives of this thesis. Initially, the climatology of South Africa is surveyed in terms of the historical understanding of the general climatology and what major weather systems impact South Africa.

The evolution of wind energy yield analysis is surveyed to understand what methods, datasets and software are relevant in the wind industry at present towards quantifying the wind energy potential of the Eastern Cape Province of South Africa.

SOMs are explored to show their general application and as a method of identifying common synoptic weather systems generated out of reanalysis datasets. This in the context of temporally linking these synoptic weather systems with energy yield from wind energy facilities with the intention of identifying which produce high wind energy in the Eastern Cape Province of South Africa.

Research being undertaken using GCMs is considered generally, but also in the context of projecting the frequency changes of high wind energy producing synoptic systems due to climate change in the Eastern Cape Province of South Africa.

Finally, the use of GCMs in projecting risk for wind energy facilities is investigated. This to understand the impact that climate change is having on such facilities and how this risk mitigation is currently being carried out but also envisaged to develop over time in South Africa.

2.2 Climatology and wind energy yield analysis in South Africa

Literature is presented here in respect to objective number 1 of this thesis, which aims to quantify the present-day wind climatology and associated net capacity factors of WEFs in South Africa's Eastern Cape Province. It is proposed that two key components are required i.e. an understanding of the fundamental weather systems affecting South Africa's wind energy and the methodology for developing accurate energy yield analyses for WEFs.

2.2.1 *Climatology of South Africa*

The seminal research regarding South African weather systems was conducted by Tyson and Preston-Whyte in their publication 'The Weather and Climate of Southern Africa', (1988). It offers an introduction to the structure of the atmosphere, and detailed, well-illustrated discussions on the physics of meteorology, measurement, weather systems, ocean-atmosphere interactions, pollution, climatic change, and forecasting in the Southern Africa region. It is still used extensively in tertiary institutions to frame understanding of Southern African climatology today. For this thesis, it has provided a basis for understanding the major high- and low-pressure systems that dominate the region as well as the resulting major synoptic weather systems moving across the area. Typically, the interaction between these high- and low-pressure systems provide the necessary pressure gradients that bring high wind speeds to the country (Tyson and Preston-Whyte, 1988). The emergence of these pressure gradients is outlined in this publication by showing how the mid-latitude cyclone weather system, emanating of the southwestern coast of South Africa. During summer, these tend to move south and in winter, the sub-tropical high-pressure cells migrate north due to friction between the cooler polar easterlies and warmer sub-tropical westerlies (Tyson and Preston-Whyte, 1988).

A recent set of studies conducted by Engelbrecht et al. (2014), and Ndarana et al., (2020), discusses the moisture fluxes associated with the ridging south Atlantic

Ocean anticyclones during summer and the origins of rainfall over South Africa's Cape south coast and concur with Preston-Whyte. Lennard et al., (2014), studies the changes in synoptic circulations to the rainfall response. These studies focus primarily on rainfall fluxes and origins and not wind speeds but do however provide a useful methodology using the SOM tool to quantify the dominant weather systems responsible for this rainfall (Engelbrecht et al., 2014, Ndarana et al., 2020, Lennard et al., 2014).

SOMs are widely used in synoptic climatology for example, the work by Hewitson et al., (2002) and Sheridan et al., (2011). Van Doan et al., (2021) makes use of SOMs in synoptic weather system typing using ERA5 mean sea level pressure. This method and tool can be repurposed to provide similar results for wind energy production. Van Aarde et al., (2023), do show the relationship between wind speed and weather systems in South Africa by also making use of SOMs however this research focuses on the variability of wind speeds and stops short of correlating this with wind energy potential which has not been accomplished yet in South Africa.

2.2.2 *Energy yield analysis*

As a result of the oil crisis in the late 1970s, economies such as the USA began diversifying their energy mix to avoid being so heavily reliant on high carbon fuels (US DOE, 1992). The U.S. Department of Energy (DOE) Wind Energy Program: 1977–1992 report (1992), outlines the drive behind growing alternative energy installations such as WEFs which in turn resulted in the need for developing methodologies for wind energy yield analysis (EYAs). As this need grew, institutions such as the U.S. National Renewable Energy Laboratory (NREL) and the Danish Technical University (DTU) developed methodologies and software to produce such EYAs. The Wind Atlas Analysis Application Program (WAsP ©), (DTU, 2020, 2022), was developed by the DTU in 1982 as the seminal piece of software for EYAs. Many variations and competitors have since entered the market such as Openwind © (UL, 2010, 2023), from Underwriter Labs or Wind Pro © from EMD.

With improved computing power and in conjunction with the European Centre for Medium-Range Weather Forecasts (ECMFs) ERA5 satellite datasets (ECMWF, 2021, Gruber et al., 2022, Hersbach et al., 2020a, 2020b), the DTU was then able to generate mesoscale wind speed maps of the globe such as the Global Wind Atlas © (Badger et al., 2022), and the Wind Atlas of South Africa (CSIR, 2019). These wind speed maps are generally used to select pre-feasibility positions for WEFs for meteorological mast installations to measure the onsite wind speeds (DTU, 2020). These wind speeds are then used in software like WAsP © in conjunction with methodologies to account for all possible losses and provide a net wind energy yield, (Wizelius, 2012).

Studies have been conducted to ascertain the wind energy potential of various countries such as for example, Frew (2017), for variable generation capacity in the USA, Charabi et al., (2019), for offshore wind in Oman and Khan et al (2023), in Thailand. In South Africa, the study by the CSIR and Bofinger et al., (2016), quantified how much combined generation from wind and solar energy could be achieved in well define spatial areas of South Africa. This study and that conducted by Van Aarde et al., (2023), stopped short however of mapping, on an hourly basis, the wind energy production to its accompanying weather system occurring at the concurrently.

2.3 Wind energy projections

Literature is presented here in respect to objective number 2 of this thesis, which aims to develop a universally applicable methodology for producing detailed projections of how the wind energy production in the Eastern Cape Province of South Africa will alter over time under different mitigation scenarios in a changing climate. To achieve this an understanding of global climate models and associated projection methodologies is required.

2.3.1 Global climate models

In 2016, the World Climate Research Programmes (WCRPs) Coupled Model Intercomparison Project Phase 6 (CMIP6) commenced (UKESM, 2022, WCRP, 2023). Preceded by CMIP3 (2004) and CMIP5 (2008), these collaborative efforts amongst climate modelling groups, provide understanding via GCMs for past, present and future climate scenarios for the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (2021), (UKESM, 2022, WCRP, 2023). Global warming levels differ per GCM and are outlined Hauser et al., (2022). Each GCM also caters for a number of Socio-Economic Pathways (SSPs) which define whether the future will be high or low carbon intensive (German Climate Centre, DKRZ, 2022). These parameters can influence the year which a GCM attains a particular warming level and how a specific parameter may change over time. Using GCMs can ultimately give an indication of how the wind speeds, and indirectly the wind energy production, will be affected by changes in the frequency of synoptic weather systems bringing high wind energy production. Eyring et al., (2016), show that the Global Climate Models from CMIP6, as opposed to CMIP5, provide enhanced model complexity, more SSPs, higher resolution data and expanded experiments however are limited in the number of experiments that provide geopotential results. With this in mind geopotential, the major parameter investigated in this thesis, is available from the core projection datasets NorESM2 (NCC, 2022), MPI-ESM1.2 (Gutjahr et al., 2018), and CanESM (Swart et al., 2019).

Other less widely used options to derive long term geopotential projection datasets include, for example, NASAs Earth Exchange (NEX) (NASA, 2024), and the ECMFs climate projection systems (ECMWF, 2021). Tian et al., (2019), make use of an observed dataset to perform a long-term study of surface wind speeds in the Northern Hemisphere from 1979 to 2016 with the results showing a decrease in the wind speeds over this time and in turn the actual energy production decreases. It also concludes that, GCMs show poor ability to predict these long-term trends if only using the wind speed parameter directly and alternative methods of ensembling using changes in synoptic type frequency may be a better alternative (Tian et al., 2019).

2.3.2 *Climate change and projections*

Internationally, GCMs have been used in various ways to investigate how synoptic weather systems change over time for example, Hope (2006), investigated changes in frequency and make up of synoptic systems influencing Southwest Western Australia whilst Teutschbein et al., (2012), applied bias correction methods to regional climate models in Sweden to evaluate their effectiveness in relation to hydrological climate change impacts. Gebraad et al., (2023), used only the wind speed parameter from an ensemble of Global Climate models run through a power curve to calculate the wind energy production change over time for early stage WEFs in the Irish Sea, Belgium and Fortaleza Brazil. This study also provides a simple Internal Rate of Return (IRR) calculation to understand the impact with and without climate change (Gebraad et al., 2023). This type of IRR analysis has not been conducted for the Eastern Cape of Southern Africa. Pryor et al., (2011), uses regional climate models to assess the long-term viability of wind energy in the USA and concludes that the variability of wind energy production is never greater than the historical variability. Carvalho et al., (2016), uses a CMIP5 GCM ensemble's wind speed parameter downscaled for the Baltic Sea and Southern Europe regions and concludes that, although the results have high uncertainty, a long-term increase is observed in the Baltic Sea region and a decrease in wind speed is observed in Southern Europe. Similar studies are conducted in Europe and China using the wind speed parameter from GCM ensembles and showing similar variability by Devis et al., (2018), Tobin et al., (2016), and Chen et al., (2012). Cradden et al., (2012), claims to have completed the first detailed assessment of the future wind climate of the United Kingdom with results showing no major change in the mean wind climate. The detail claimed is however contradictory to the fact that only once GCMs wind speed parameter is used (Cradden et al., 2012). The author does however acknowledge this limitation and suggests using as large an ensemble of GCMs as possible (Cradden et al., 2012). Nolan et al., (2012), also uses a regional climate model ensemble to downscale the wind speed parameter to the domain of Ireland with results showing a decrease in summer and an increase in winter. Chang et al., (2015), uses a similar method of downscaling for Taiwan showing an upward trend in wind speeds. This a more robust method than simply extracting the wind speed

parameter from the GCM however the inherent uncertainty is still present even when downscaling (Chang et al., 2015).

General changes in regional atmospheric models in South Africa due to climate change signals are investigated by Engelbrecht et al., as early as 2009, with follow up studies by Archer et al., in 2018. Engelbrecht et al., (2012), and Pinto et al., (2015), which use the method of calculating the change in the frequency of occurrence of the trained SOM result (i.e. a set of synoptic scale circulations) to project the change in closed low-pressure systems which in turn show the change in extreme rainfall events over Southern Africa. Engelbrecht et al., (2015), employ a similar approach but look rather at the rapidly rising temperatures over southern Africa. The CSIR has used GIS to visualise detailed projections of future climate for temperature and rainfall, (CSIR, 2022a), up to 2050 in their 'Green Book'. This methodology has not been applied to wind energy production in South Africa.

2.4 Impact and mitigation of climate change on WEFs

As a result of thesis objective 1 and 2, it is possible to now identify literature pertaining to objective 3 of this research, which aims to facilitate the future establishment of adaptation and risk mitigation measures for addressing climate change impacts on the renewable energy sector in South Africa.

Internationally, climate change risk mitigation is growing with companies like Det Norske Veritas (DNV), (DNV, 2022) and Climate Scale (Gebraad et al., 2023) already providing a service to the wind energy industry to foresee and mitigate climate change risk for WEFs. Their focus is wholistic and Lopez from Climate Scale (2023), presented a proposal for standardising the methodology for climate risk reporting at Wind Europe 2023. According to Lopez, climate risk is quantified according to temperature, wind, water and solid mass with a key consideration being the uncertainty associated with each of these aspects (Climate Scale, 2023). Solaun et al., (2020), outlines key climate change aspects affecting WEFs such as changes in wind speed, diurnal and seasonal distribution of wind, changes in

temperature, sea level rise and extreme weather events by investigating an ensemble of WEFs in the USA, Europe, South America, China and South Africa. Pryor et al., (2013), provides a similar synopsis of how spatio-temporal changes in wind resource can impact the positioning and selection of wind turbine generators (WTGs). The results show that generally the predictions are within the conservative design uncertainty of the WTGs however more research is required for developing regions globally (Pryor et al., 2013). This is particularly true for South Africa in that there is not currently any long-term justification for the selection of the position of Renewable Energy Development Zones (DFFE, 2021). Pryor et al., (2013), also discusses vertical wind shear in terms of climate change impact on turbulence intensity directly affecting the types of WTGs that OEMs will propose for a WEF.

Financial risk is investigated by Hdidouan et al., (2016), who provides a study on the impact of climate change on the Levelised Cost of Energy (LCOE) for WEFs with results highlighting the fact that financial risk impacts must be adopted into policy to build resilience in energy systems with the suggestion to include climate change impact in EYAs as a loss or uncertainty. Solaun et al., (2020), continues this theme to investigate four WEFs in Spain in terms of operating margins and investment in WEFs. The study relies on wind speed from a three GCM ensembles converted to production data and concludes that production variations can be up to 8% (Solaun et al., 2020). Again, the study does not consider the synoptic circulations and their frequency change but rather the wind speed parameter directly from the GCM ensemble (Solaun et al., 2020).

Wachsmuth et al., (2013), investigates the impact on wind energy generation in Northwest Germany with an emphasis on grid build out. The conclusion is that robust and well-established transmission grids including battery storage will bring the stability needed for the rollout of renewable energy (Wachsmuth et al., 2013).

2.5 Conclusion

Quantifying the wind resource in South Africa has, to date, been conducted using measured wind speed and wind direction data from the Wind Atlas of South Africa (WASA) and in some cases the South Africa Weather Service (SAWS) (CSIR, 2019). This data has also been used to validate high-resolution regional model simulations (of wind patterns at the meso-scale) of the wind resource such as the Global Wind Atlas © (Badger et al., 2022). Thus, the use of GCMs to describe the wind resource in South Africa has been limited, with inadequate work considering future projections.

Following a review of the literature relating to objective number 1 of this thesis, although similar studies have been conducted for other parameters such as temperature and rainfall, it is concluded that no work has been done to quantify, in detail, wind energy yield potential of the Eastern Cape Province of South Africa as it relates to the accompanying synoptic weather systems of the region. Some work has been conducted using SOMs however this research focuses on the variability of wind speeds and stops short of correlating this with wind energy potential.

Following a review of the literature relating to objective number 2 of this thesis, the emergence of two methods is observed for projecting wind energy production changes namely 1) using GCMs wind speed parameter directly passed through a WTG power curve to calculate the wind energy produced or 2) using the long-term change in frequency of synoptic weather systems that are proven to produce high wind energy. The latter, although more time and resource intensive due to the training of the SOM simulations and the numerous correlations required, shows more positive results since it takes into consideration the mesoscale changes in how large synoptic weather systems perform. Furthermore, it is accepted that a GCM ensemble method investigating large synoptic system frequency changes is likely to produce reliable results (Engelbrecht, C. et al., 2013, 2014). The GCMs from CMIP6, as opposed to CMIP5, are shown to provide enhanced model complexity, more SSPs, higher resolution data and expanded experiments. It is concluded that no work has been done to develop a universally applicable

methodology for producing detailed long-term projections of how the wind energy production in the Eastern Cape Province of South Africa will alter over time under different mitigation scenarios in a changing climate. Furthermore, although done in other regions, no quantification of the impact on IRR for wind farms has been conducted in the Eastern Cape of South Africa.

Following a review of literature relating to objective 3 of this thesis, Globally and locally in South Africa, the literature shows a growth in renewable energy installations. This poses a need for understanding and predicting the performance of these variable forms of energy with wind energy, in particular, being heavily reliant on interactions of large synoptic weather systems to produce the resource. Climate change impacts on renewable energy plants and risk mitigation are key requirements for safeguarding South Africa's renewable energy future but are not, to date, been sufficiently outlined using scientific methods according to the literature.

3. CHAPTER 3: Spatial area of interest

Within the context of Africa, South Africa displays a strong wind resource with parts of the country achieving average annual wind speeds higher than 8 m/s at 100 m (CSIR, 2019). This is comparable to that achieved for similar latitudes in the Northern hemisphere as can be seen from the Global Wind Atlas in Figure 3-1 (Badger et al., 2022).

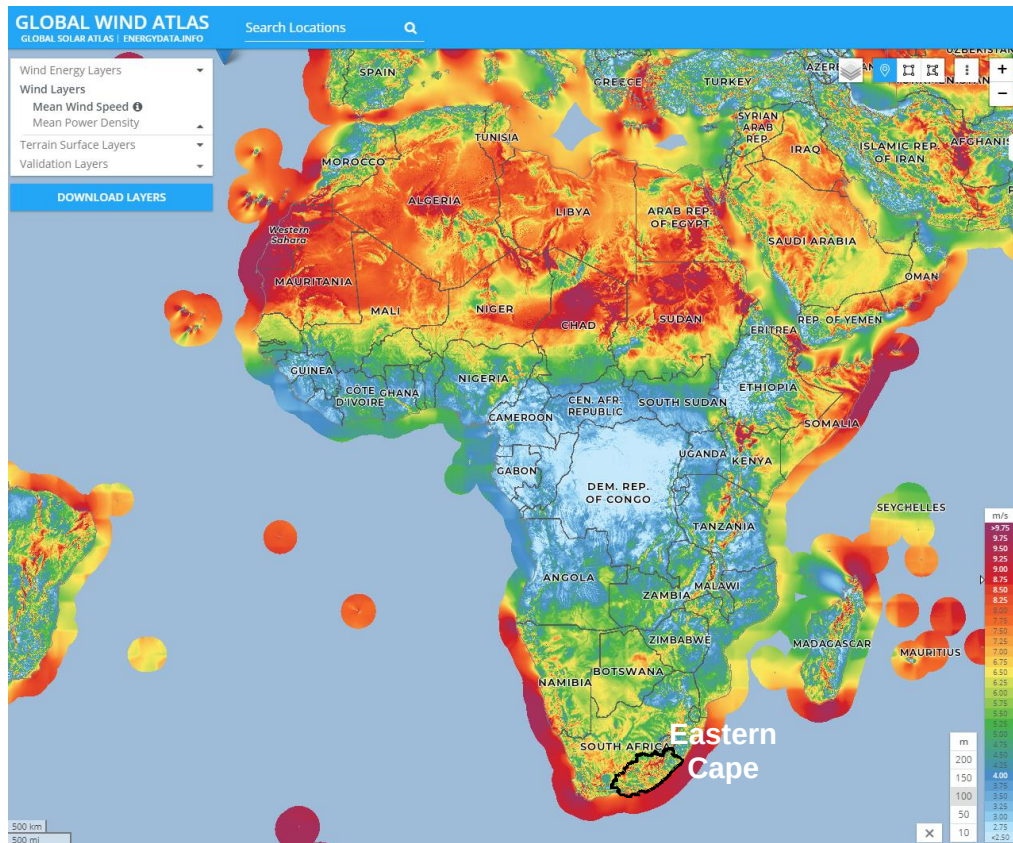


Figure 3-1: Wind resource for the African Continent showing spatial focus area in South Africa (Badger et al., 2022)

To achieve a study using SOMs the entire South African land mass is too large in terms of the computing power available and thus it makes sense to focus on the province with the most favourable wind resource at present i.e. the Eastern Cape Province. With additional computing power it will be possible to roll this out for the whole country or other global focus areas in future.

3.1 Eastern Cape climatology

The Eastern Cape province of South Africa is located in the southeast of the country with Indian ocean to its east. The province benefits from significant wind energy potential due to the Southern Ocean's westerly wind regime and the strong pressure gradient between the well-developed high-pressure cells in the north and low-pressure cells to the south (Tyson et al., 1988). The southern parts of the province experience all year-round rainfall while the northern interior experiences summer rainfall influenced by tropical troughs and westerly waves (Engelbrecht, C. et al., 2014). Winter rainfall originates from mid-latitude cyclones that brush the southern tip of South Africa as well as the cut off lows that bring extended periods of rainfall (Engelbrecht, C. et al., 2014). During the presence of the cut off lows, wind speeds more than 15 m/s are not uncommon (Tyson et al., 1988).

The WASA maps are mesoscale representations of the whole of South Africa and give only a snapshot in terms of annual average power density and wind speeds validated by 19 meteorological masts having been measuring from 2009 (CSIR, 2019).

To better understand the wind climate conditions as they change throughout the year, a pilot study prior to the broader study provided later in this thesis, investigated the annual 10-minute average wind speed and direction timeseries for the years 2009 to 2013 (Bofinger et al., 2016). Figure 3-2 shows four representative positions that have been chosen within the high-power density vein in red, for Eastern Cape Province (Bofinger et al., 2016).

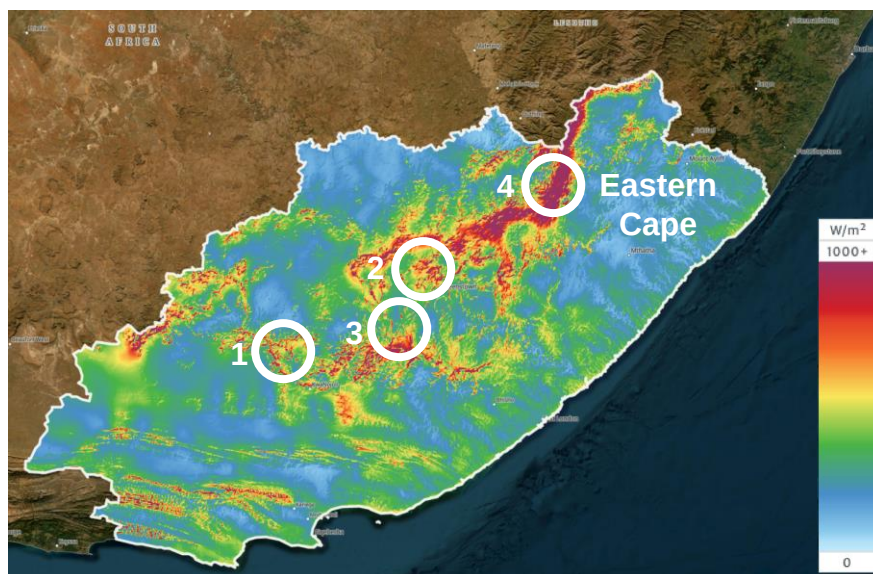


Figure 3-2: Indicative Eastern Cape Wind Climate Sites within the GWA Power Density Map (Badger et al., 2022) (Global Wind Atlas ©)

The results of this analysis are shown in the table below.

Table 3-1: Wind Climate Analysis of four sites in the Eastern Cape Province (Bofinger et al., 2016)

	Average Long Term Wind Speed (m/s)	Net Capacity Factor %	Windiest Months	Least Windy Months	Dominant Wind Direction/s
Site 1	8.4	51%	Jun, Jul, Aug	Jan, Feb, Mar	SW / NW
Site 2	7.9	49%	May, Jun, Aug	Jan, Feb, Mar	NW
Site 3	8.6	55%	Jun, Aug, Sep	Jan, Feb, Mar	WSW
Site 4	10.1	61%	May, Aug, Sep	Jan, Feb, Mar	NW

From the results presented in the table above, these four selected sites have average annual wind speeds greater than 7.9 m/s at 120 m above ground level (AGL). which are deemed extremely viable at utility scale (Bofinger et al., 2016). Accompanying these excellent wind speeds are very attractive net capacity factors. Anything higher than 50 % is extremely competitive in the future bid rounds of the REIPPPP (ESI, 2023).

3.2 Energy availability in the Eastern Cape

At 82%, The Eastern Cape Province has the lowest electricity access rate in South Africa with rural communities facing significant energy poverty (Lesala et al., 2023). Grid unavailability is projected to remain in place for up to 15 years (Lesala et al., 2023). Traditional energy resources such as firewood are used for day-to-day cooking and pose a health risk (Lesala et al., 2023). Despite programs such as the Free Basic Alternative Energy program and solar home system subsidies, challenges remain in alleviating the energy poverty for low-income households in these areas (Lesala et al., 2023). This is ironic and in stark contrast to the fact that the Eastern Cape has the most installed WEFs in South Africa (Earthworks Magazine, 2022) and the highest potential for further installations. Compounding this fact is that there is no available grid capacity for new WEF connections to the grid (Eskom, 2015).

3.3 Wind energy potential of spatial area of interest

The Eastern Cape has high wind energy potential corroborated by the REIPPPP planned and installed wind farms in Figure 3-3 where 17 wind farms are located in the Eastern Cape.

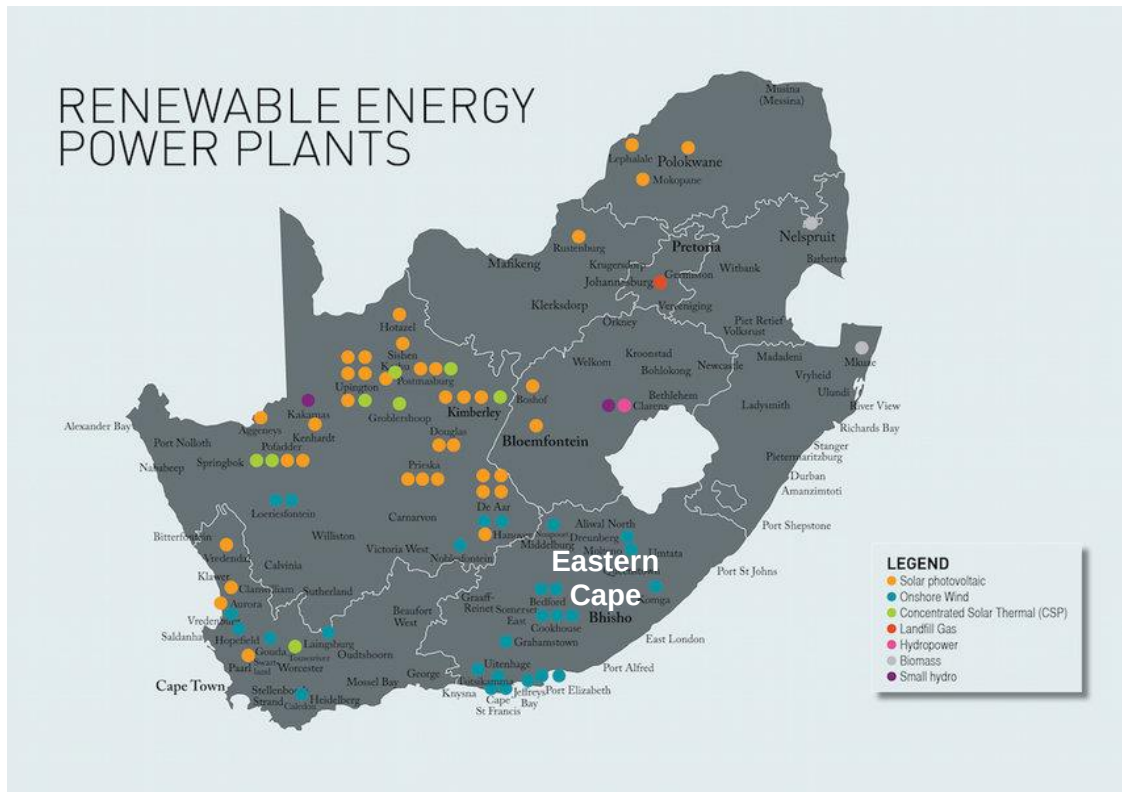


Figure 3-3: South Africa REIPPPP planned and installed capacity (Earthworks Magazine, 2022)

The Global Wind Atlas power density¹ map (Figure 3-4) provides further justification for this conclusion with the Eastern Cape displaying annual average wind power densities in the order of 800 – 1000 W/m² at 100 m (Badger et al., 2022).

¹ Power density is the mean annual power available per square meter of swept area of a suitable WTG. The red areas show power densities more than 1000 W/m² which is exceptional.

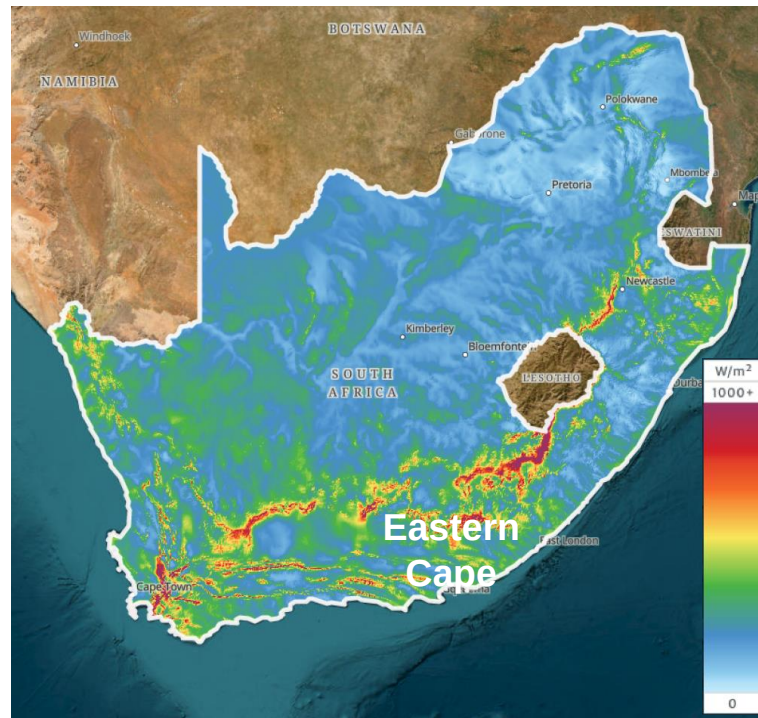


Figure 3-4: Wind energy power density map [W/m-2] (Badger et al., 2022) (Global Wind Atlas ©)

Taking this further, the high resolution WASA wind speed map Figure 3-5, shows a significant part of the Eastern Cape Province having annual average wind speeds higher than 8 m/s making it viable for utility scale wind farm sites (CSIR, 2019).

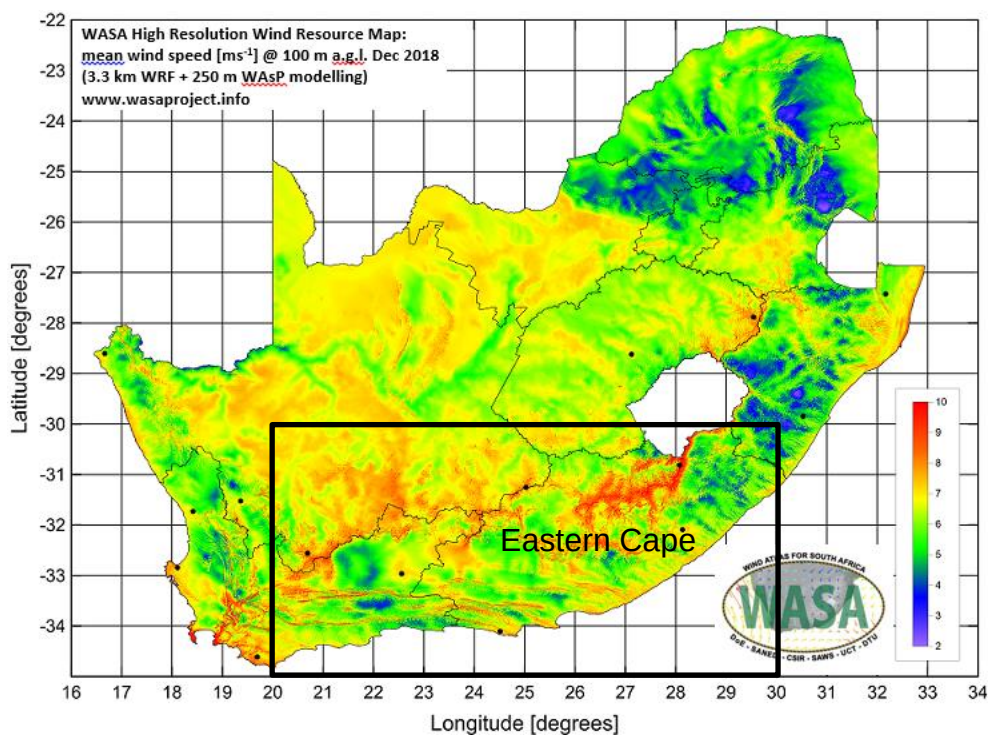


Figure 3-5: WASA wind speed map showing spatial focus area (black rectangle) (CSIR, 2019)

4. CHAPTER 4: Methodology

The proposed methodology outlined in Chapter 5, 6 and 7 of this thesis is carried out in seven major steps as shown in the flow diagram Figure 4-1, illustrating order and data sources respectively.

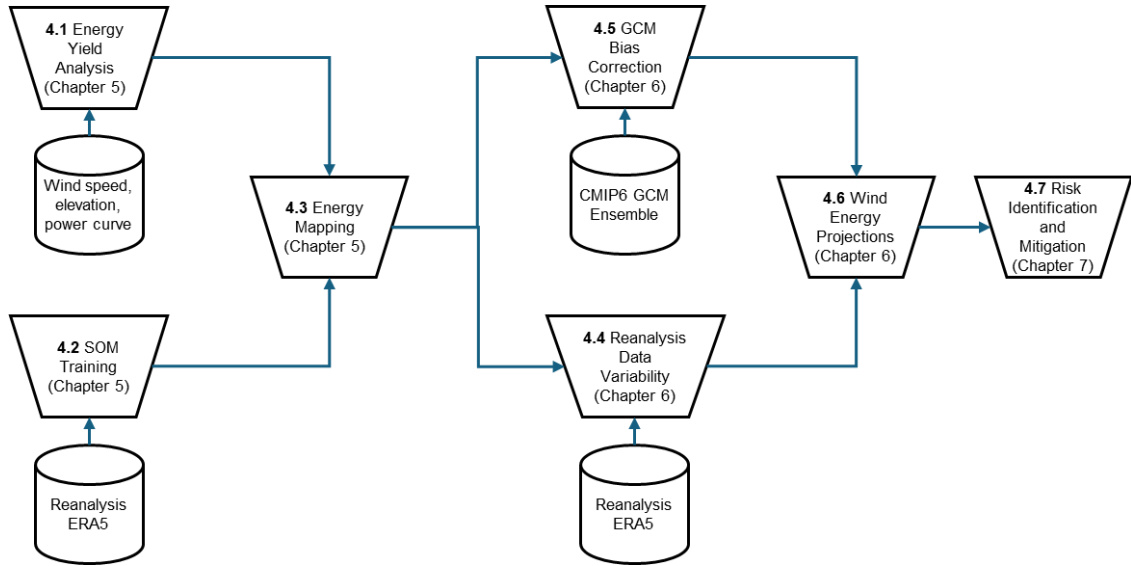


Figure 4-1: Methodology flow diagram

Ethics clearance is not applicable to this methodology since it is based exclusively on manipulation of observed and freely available datasets. Here follows a summary of the sub-steps. More detail is presented in each of Chapters.

4.1 Energy yield analysis

A crucial part of the energy production calculation for a WEF is a sufficiently long period of observed wind resource timeseries, derived from measurement instruments mounted on a meteorological mast on the site. This observed wind resource data generally needs to be properly quality controlled to make sure there are no anomalies that could impact the energy production calculations. Energy yield analysis can be accomplished in different ways but this methodology loosely follows four stages as outlined by the DTU in 1982 when it released the first version of WAsP © (DTU, 2020, 2022). Initially, and preferably, observed meteorological

data must be acquired as the basis for the EYA and then the WEF can be modelled typically in proprietary software such as WAsP © or Openwind ©. Considering relevant losses such as electrical, availability, curtailment etc. the net energy production can then be calculated. This then allows the generation of an hourly production timeseries typically called an '8760'.

4.2 SOM Training

This method is based on the work done by Engelbrecht et al., (Engelbrecht, C. et al., 2014), who related Eastern Cape rainfall patterns to synoptic types using SOMS. It was decided to use 35 nodes (representing 35 characteristic synoptic weather type circulation patterns), derived from the ERA5 reanalysis dataset. The SOM was developed over the Eastern Cape spatial area of interest.

SOMPAK © was used to produce the final trained SOM for this study (Kohonen et al., 1996). The software was developed by Kohonen and is based on an unsupervised neural network that reduces a large dataset to lower input dimensionality (Kohonen et al., 1996). Data preparation is required specific to what the software requires following which SOMPAK © can be run to develop the trained SOM result which is sense checked using the Sammon map (Sammon, 1969).

4.3 Energy mapping

Following the process of characterising the trained SOM consisting of 35 synoptic weather types, each node can be associated with a to commonly occurring synoptic weather type for the spatial area of interest and then the resultant energy production associated for each can be quantified. This is done via an energy mapping process which entails matching the energy production to each node in the timeseries. This method is derived from that used by Engelbrecht et al.,

(Engelbrecht, C. et al., 2014), however it relates wind energy production rather than rainfall to a trained SOM.

4.4 Reanalysis data long-term variability

To rule out any possible long-term variability in the observed ERA5 dataset with respect to node frequency, the 2000 – 2009 profile must be compared with the 2010 – 2019 profile (i.e. generally, the observed dataset must be compared with an adjacent decade to rule out any variability). To do this, the ERA5 geopotential dataset for 2000 to 2009 is acquired and regridded to 1° to extract all timestamps. The greater spatial focus area of $0^\circ/50^\circ$ longitude, $-10^\circ/-50^\circ$ latitude and the EC spatial focus area $20^\circ/30^\circ$ longitude, $-30^\circ/-35^\circ$ latitude are then extracted so that the EC area average can be subtracted from the greater spatial focus area. The Pearson correlation is then run to determine the frequency of synoptic types when compared to the original trained SOM to make any adjustments if necessary.

4.5 GCM frequency correction

To determine how well the global climate models predict the occurrence of the SOM patterns extracted from the ERA5 datasets, a similar process is followed to the previous step however instead of ERA5 variability in another decade, the GCM is compared with the observed frequency. To achieve this, the GCM must be obtained from 2010 to 2100 and the concurrent period extracted and regridded to 1° to extract all timestamps. The greater spatial focus area and the EC spatial focus area are again extracted so that the EC area average can be subtracted from the greater spatial focus area. The Pearson correlation is then run to determine the frequency of synoptic types in the GCM when compared to the original trained SOM. This facilitates the calculation of the frequency correction required to adjust the GCM to the observed frequency of the trained SOM.

4.6 Wind energy projections

Once the GCM frequency has been corrected, it can then be projected to determine the frequency of the synoptic types and in turn the energy production for future decades. The remaining GCM data for years 2020 to 2100 is prepared and node frequencies are calculated with applied correction factors and the specific energy production is applied to the calculated frequency of the SOM nodes to determine the specific energy production for every year until 2100. Once again, this method is derived from that used by Engelbrecht (Engelbrecht, C. et al., 2014), however it projects changes in wind energy production rather than rainfall to a trained SOM.

4.7 Identification of adaptation measures

Given the state of South Africa's energy sector, there is a clear need to develop long-term renewable energy forecasting capability to properly define the risk and facilitate the strategic development of specific adaptation measures to safeguard renewable energy installations in the long term.

A proposal for standardising climate risk reporting was presented at Wind Europe 2023 by Lopez et al., from a Climate Scale (Lopez et al., 2023) to quantify climate risk in relation to renewable energy production plants according to temperature, wind, water and solid mass with a key consideration being the uncertainty and the financial risk associated with each of these aspects. Furthermore, these aspects can be grouped into impact categories such as revenue, operation and maintenance and infrastructure (CAPEX). This generic method is adopted for application to the spatial focus area and eventually South Africa.

CHAPTER 5: PAPER 1 - Wind Energy potential of weather systems affecting South Africa's Eastern Cape Province

Published by Theoretical and Applied Climatology

NOTE: The published format of this paper is included in Appendix H. The format provided here is amended to allow for continuous formatting and chapter, table and figure numbering in the overall thesis. The content remains exactly the same as the published paper.

Impact Factor 3.41

Date Submitted: 1 June 2023

Date Published: 2 January 2024

Submission ID: a73aad65-7571-4b3a-85b3-2aa805a57013

Published Article: <https://doi.org/10.1007/s00704-024-04830-z>

Contributions:

Gregory Landwehr (80%)	Francois Engelbrecht (12%)	Chris Lennard (8%)
• Conceptualization • Data curation • Formal analysis • Investigation • Methodology • Project administration • Writing - original draft • Writing - review & editing	• Conceptualization • Funding acquisition • Methodology • Project administration • Supervision • Writing - review & editing	• Conceptualization • Methodology • Supervision • Writing - review & editing

5. Paper 1 (Chapter 5) in the context of Paper 2 (Chapter 6) and Paper 3 (Chapter 7)

Paper 1 (Chapter 5) proposes a methodology for quantifying the major large scale synoptic circulations that are responsible for bringing the most wind energy to spatial focus area of South Africa's Eastern Cape Province.

SOMs are applied to daily low level circulation fields over the period 2010-2019 to identify these predominant synoptic weather types that affect wind energy in the Eastern Cape of South Africa.

With each of these synoptic circulation types, a probability density function of daily wind energy profiles is derived and associated with each of the four key wind energy production locations in the Eastern Cape. In this way, the role of each prevailing synoptic type in providing the present-day wind energy production of the Eastern Cape is described.

These results are used in Paper 2 (Chapter 6) to develop projections in wind energy potential for the spatial focus area under climate change.

Abstract

As a percentage of the total global energy supply, wind energy facilities could provide 10% of the total global energy supply by 2050 (IEA World Energy Outlook, 2023). Considering this, a just transition to renewable and sustainable energy in South Africa is a genuine possibility if steps are taken to achieve this. The Eastern Cape province exhibits a strong wind resource which can be exploited towards expediting such a Just Energy Transition.

No research and related modelling have, to date, been undertaken in quantifying and relating the detailed P50 Energy Yield Analyses of representative Wind Energy Facilities in temporal and spatial dimensions to the occurrence of specific synoptic types in South Africa.

To quantify this energy meteorology climatology for a suitably sized geospatial area in the Eastern Cape province of South Africa (spatial focus area, latitude -30 to -35; longitude 20 to 30), the approach of using SOMs is proposed. These maps are used to identify the most common synoptic circulation types occurring in the Eastern Cape and can subsequently be mapped onto an equivalent time resolution wind energy production timeseries calculated based on probable wind energy facility sites.

This paper describes comprehensive methodologies used to model the wind energy facilities, calculate with high confidence the P50 energy production, and then identify the predominant synoptic weather types responsible for the wind energy production in this spatial focus area. After quantifying the energy production, running a SOM software generates a purposely selected thirty-five node map that characterises archetypal synoptic patterns over the ten-year period. The synoptic types can be ranked by highest energy production.

It is shown that in this spatial area, monthly wind energy production is higher during the winter months. When the well-established high-pressure cells move northward synoptic types associated with higher energy production are frequent and include tropical and temperate disturbances across South Africa, patterns resembling a ridging anticyclone off the west coast of South Africa and low-pressure cells occurring to the north and south. Low energy producing patterns

show characteristics of the high-pressure cells moving southwards producing fine weather and mildly disturbed conditions.

The purpose of this methodology is that it provides the foundation required to derive long term frequency changes of these synoptic weather systems using Global Climate Model ensembles and thus changes in wind energy production.

Keywords:

Onshore wind energy facilities, Synoptic types, Wind Energy Meteorology, Self-organising maps.

5.1 Introduction

In South Africa, a seminal paper on Renewable Energy, written in 2003, recognised that the long-term potential of renewable energy is substantial (RSA DoME, 2003b). Wind energy has also been given priority by the Integrated Resource Plan (IRP) (RSA DoME, 2019). This positive outlook for renewable energy, in particular wind energy, in South Africa requires long-term strategic planning to realise that potential.

A single WEF typically takes two to four years to build (RSA DoME, 2022) and integrating such facilities with existing Distribution and Transmission networks requires consultation with Utilities on tie in solutions whilst always referencing their Generation Connection Capacity Assessment (GCCA) (Eskom, 2015). WEF development is dependent on the strength of the wind resource itself and the process involved requires onsite measurement instruments as well as well-defined statistical techniques to characterise the wind resource. As a rule, banks and other investors demand at least one year of measured wind resource data and an independent third-party evaluation from a well-established energy yield consultant before committing investment to a new WEF.

As part of deciding the location of a new WEF, climate variability and change should be considered. Important is optimal energy production over the lifespan of the generators and associated PPA, which may well be twenty years or longer. Such planning extends to the reuse of the site after the WTG lifespans are over implying, the need to include climate change assessments beyond the near-term (the next twenty years).

In this study, the Eastern Cape (EC) of South Africa is selected as the area of interest since it has strong potential for WEF development with annual average wind speeds of greater than 7.2 m/s (at 62 m, the local Wind Atlas of South Africa (WASA) masts highest anemometer) and net capacity factors above 40 % at the sites investigated in this paper. The province has and is expected to be extremely competitive in the future bid rounds of the Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) and private sector PPAs (RSA DoME, 2023a).

To characterise the wind potential of the Eastern Cape in more detail, four potential WEFs are modelled, each purposefully located close to the WASA (CSIR, 2019) meteorological masts. These masts provide ten years of ten-minute average wind resource measurements, from 2010 to 2019. This allows for the energy production at P50² level to be calculated with high certainty given the ten-year measurement period.

To quantify the energy-meteorology climatology of the Eastern Cape province of South Africa a synoptic typing methodology is used to objectively identify the main synoptic weather systems that provide wind potential to the province. Characterising these synoptic types and the resultant energy production associated with each can inform WEF siting for both the current climate as well as future climate that may change due to global warming.

This paper begins by presenting the background information in section 2 which is necessary to generate the results. Methodologies used in the study are presented in detail in section 3 and the results and discussion follow in section 4, with conclusions drawn in section 5.

5.2 Background

5.2.1 South African electricity supply system

South Africa exhibits one of the most carbon intensive electricity supply systems in the world and is currently striving towards a 'Just Energy Transition' which is less carbon-intensive (European Commission, 2022). South Africa's power Generation, Transmission and Distribution systems are dominated by Eskom³. The parastatal generates 90% of South Africa's electricity with a current power plant capacity for South African consumption of approximately 46.5 Gigawatts (GW) most of which

² P50 Energy Yield: The net AEP value is considered the 'P50' energy yield value and constitutes the Gross AEP value less losses that has the probability of being exceeded by 50% of all AEP's that could be possible for the site involving the uncertainties associated with the estimate.

³ Eskom: Eskom Holding SOC. Ltd. is South Africa's primary electricity supply utility.

comes from coal (Eskom, 2023a). This varies at any one time due to electricity trading with neighbouring countries and issues such as load shedding and unforeseen plant maintenance. As per the latest South African census, the electrification ratio in South Africa is at 87% (Statistics South Africa, 2011).

During the last decade South Africa has developed approximately 6 GW of combined Wind, Solar Photovoltaic (PV) and Concentrated Solar Power (CSP) (CSIR, 2020). Projections made by the Department of Mineral Resources and Energy (DMRE) show that the electricity generation capacity of South Africa could rise to 109 GW by 2050 with 33 % (capacity and electricity production) coming from wind alone (RSA DoME, 2019). If such a change materialises, it will have extensive benefits beyond energy generation and would contribute to South Africa's emissions reduction efforts.

5.2.2 WEF siting

Of course, WEF siting can follow different methodologies however the following description provides a general overview of the major steps that any WEF siting exercise will employ. Initially, mesoscale average annual wind speed and power density⁴ maps are used to select pre-feasibility positions for WEFs. Once a pre-feasibility position is selected, it is scrutinised against a set of pre-feasibility criteria such as proximity to the electrical grid; avifaunal/faunal no-go areas; protected flora areas, proximity to existing buildings and infrastructure and road access.

Once the site passes this screening, feasible wind turbine layouts are created based on wind flow maps which are created using the onsite measurement data. The WEF layout design is undertaken using specialised WEF modelling software (sometimes requiring computational fluid dynamic analysis for complex terrain) which considers terrain, roughness, and wake losses. Then, high level net capacity factor (NCF⁵) and AEP⁶ calculations are completed to verify the attractiveness of the site. These

⁴ Power Density: mean annual power available per square meter of rotor blade swept area of a suitable WTG.

⁵ Net Capacity Factor: the actual annual net energy yield / theoretically possible annual energy yield if the plant ran at full capacity all year around. $NCF = \text{Actual Energy Generated less all losses (MWh)} / (\text{Plant Capacity (MW)} \times \text{Time Period (h)})$

⁶ Annual Energy Production: actual annual gross energy production less losses.

calculations are based on at least one year of observed measurements from the site.

5.2.3 Geospatial area of interest

The Eastern Cape Province of South Africa (Figure 5-1) has a strong potential for wind energy. The WASA map (CSIR, 2019) shows a significant part of the Eastern Cape Province having annual average wind speeds higher than 7-8 m/s and accompanied by wind power densities in the order of 300 – 600 W/m². This makes the Eastern Cape a viable location for utility scale wind farms. As a reference dataset for selection of the spatial area of interest, WASA is an important reference. Similar Wind Atlases have been developed to provide comparable insights globally (Hahmann et al., 2020, 5.40].

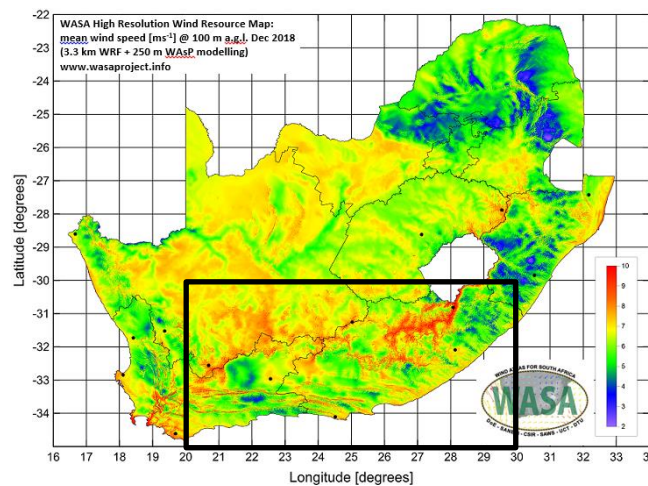


Figure 5-1: The geographic location of the study region within South Africa using the WASA wind speed map (colour bar shows annual average wind speed in m/s) (CSIR, 2019)

Accompanying these high annual average wind speeds are very attractive NCFs which can range between 35 – 45 % for the Eastern Cape and have been extremely competitive in the past bid rounds of the REIPPPP (RSA DoME, 2023a). In contrast to this, similar quality sites (Global Wind Atlas, 2023) with high density of WEFs installed exist in North Brazil (~45% NCF), the Egyptian coast of the Gulf of Suez (~50% NCF), Northern Germany (~40%) and South India (~40%).

Four potential WEF sites (Figure 5-2) have been selected to adequately cover the selected area of interest and have been chosen due to their proximity to four WASA

masts. Furthermore, they are named after the WASA masts from which the energy production timeseries is derived, WM07 (-32.967°, 22.556°), WM08 (-34.110°, 24.514°), WM09 (-31.252°, 25.031°) and WM10 (-32.092°, 28.136°) and are located between 5 to 10 km from their namesake WASA mast to the outermost WTGs. Energy production at P50 level can thus be calculated with high confidence since it is based on 10 years of high-resolution wind resource measurements from 2010 to 2019 taken from the WASA.

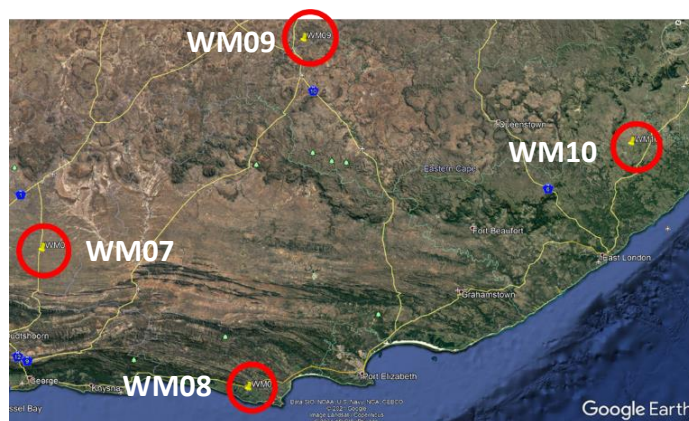


Figure 5-2: WEF Geographical positions within the geospatial focus area

The general WEF and WTG specifications used for the modelling are as follows:

Table 5-1: WEF General Specifications

WEF Capacity: [MW]	Between 148.5 and 192.5
Wind Turbine Generator Type and nameplate capacity:	3-Bladed, horizontal axis, 5.5 MW
Hub Height: [m]	120 AGL
WTG Rotor Diameter: [m]	155
Number of WTGs:	Between 27 and 35
Assumed voltage connection level: [kV]	132

5.2.4 Synoptic-scale weather systems impacting on the Eastern Cape

Located in Southern Africa, south of 30 °S, the climatology of the Eastern Cape is determined by a range of different weather systems that originate in climatological circulation zones including Southern Hemisphere westerlies, the Southern Hemisphere subtropics, and the African tropics. The coastal areas of the province are in fact a year-round rainfall zone (Engelbrecht, F. et al., 2015), where cold fronts from the westerlies in winter alternate with thunderstorm producing weather systems in summer to bring all-year rainfall.

The most important synoptic-scale weather systems determining the province's climatology, in terms of both rainfall and wind, are mid-latitude cyclones, ridging high-pressure systems, cut-off lows and tropical temperature troughs. These weather systems introduce some meso-scale circulation patterns such as berg winds, which are also important in terms of the wind climatology.

5.2.4.1 Mid-latitude cyclones and cold fronts

Key to Eastern Cape's wind climatology is the frequent passage of mid-latitude cyclones in the Southern Ocean to the south, the cold fronts embedded within these systems, when occurring at sufficiently northerly latitudes, bring distinct wind patterns to the Eastern Cape. Ahead of an approaching cold front, winds are dry and from the northwest, whilst cool or cold high southwesterly winds blow behind the front. These frontal systems are positioned more Equatorward in winter and occur more frequently and intensely during these months. They can on occasion penetrate deep into the southern African interior during 'cold snap' events, and substantially increase the energy demand in order to achieve human comfort (Tyson et al., 1988).

5.2.4.2 Ridging Anticyclones

The South-Atlantic Ocean High typically ridges in behind cold fronts affecting the Cape south coast regions of South Africa, including the Cape south coast (Ndarana et al., 2020). The ridging process initially strengthens the southwesterly flow behind the cold front, but as the process continues the flow can become pronounced southeasterly. Such ridging high-pressure systems are consequently important sources of not only wind energy for the Eastern Cape, but also of moisture and

rainfall (Engelbrecht, C. et al., 2014). Rainfall can be particularly heavy if the system co-occurs with a cut-off low (Engelbrecht, C. et al., 2014).

5.2.4.3 Upper-air troughs and cut-off lows

All mid-latitude cyclones are three-dimensional weather systems, with upper air troughs typically occurring to the west of the surface cold front, and with rainfall occurring to the east of the upper air trough. When an upper air trough becomes separated or 'cut-off' from the westerly wind regime, it is referred to as a 'cut-off low'. The generally slow-moving cut-off lows are responsible for many of the flood producing rains in South Africa, including the Eastern Cape (Engelbrecht, C. et al., 2013, Engelbrecht, F. et al., 2015). Their frequency peaks in March to May and September to November with lower frequency between December and February (WASA, 2023). Cut-off lows and upper-air troughs frequently cause several days of cloud cover, implying their indirect importance to the wind-energy sector (i.e. via reduced solar potential). Moreover, cut-off lows are associated with pronounced southeasterly flow over the Eastern Cape (Engelbrecht, F. et al., 2015).

5.2.4.4 Coastal Low and Berg Wind

Several meso-scale weather systems and phenomena induced by the synoptic-scale flow also impact on Eastern Cape climatology. Coastal lows form in the northwesterly flow ahead of an approaching cold front due to the generation of cyclonic vorticity when air descends from the South African plateau. They are associated with strong meso-scale pressure gradients with northwesterly flow to the east, and southwesterly flows to the southwest of the centres of these systems (Tyson et al., 1988).

A further mesoscale phenomenon associated with the coastal low and approaching cold front, typically occurring in winter, is the 'Berg winds' that form when northwesterly winds descend over the southern escarpment and warm adiabatically to produce high surface temperatures over the Eastern Cape. These Fohn-type winds (Tyson, 1964) occur most commonly in winter due to the relatively high frequency of passing frontal systems during this season.

5.2.4.5 Temperate disturbances in the westerlies

Fine-weather and mildly disturbed conditions over the Southern African interior occur in association with large subtropical high-pressure systems centred over the subcontinent. These systems produced fine, clear conditions and little or no rainfall, and impact on the northern interior regions of the Eastern Cape. The frequency of occurrence of anticyclones reaches a maximum over the interior plateau in June and July with a minimum during December.

5.2.5 Wind farm modelling software

Two different tools, Wind Atlas Analysis and Application Programme (WAsP ©) and OpenWind ©, have been utilised to calculate the energy production at each WEF site to provide further robustness to the results. Both are industry leading tools used for wind data analysis, wind atlas creation, wind farm energy yield analysis and siting of WTGs. Note that steps 3 and 4 in section 3.1 can be undertaken automatically in Openwind © if input loss and uncertainty values are setup within the software.

5.2.5.1 WAsP ©

As per the methodology outlined in preceding sections, the linear downscaling software WAsP ©, has been used in a semi-manual approach to generate AEP for each site. The spatial and temporal distribution of the wind resource is provided in the form of a Wind Resource Grid (WRG) and uses a virtual WTG. The AEP results are then post processed using bespoke built spreadsheet calculators (DTU, 2020).

The wake loss model used is Modified Park (Park 2) using a wake decay constant of 0.09 (UL, 2010, 5.9].

5.2.5.2 OpenWind ©

Calculating the expected energy production of wind turbines in an array is the basic function of Openwind © which follows in principle the same steps outlined in steps 3 to 4 of section 3.1 above and uses a mass consistent approach. The

spatial and temporal distribution of the wind resource is also provided in the form of a wind resource grid and the characteristics of the WTGs with loss assumptions complete the main input elements for the calculation (Engelbrecht, F. et al., 2015).

Although there are many options, the wake loss model used is also Modified Park to remain consistent with WAsP © and uses a wake decay constant of 0.09 (UL, 2010), 5.9].

5.2.5.3 Validation of the WEF modelling software

To verify that the equations and assumptions used in the OpenWind © energy production calculations, AWS Truepower has carried out a comprehensive validation exercise involving 20 real-world wind projects, using as a control the WindFarmer program of Garrad Hassan and Partners, Ltd. (UL, 2010). A comparison of the energy production results is supplied in section 4.2 for both WAsP © and Openwind © at the sites chosen to provide confidence that similar results are obtained from the different software.

5.2.6 Self-Organising Maps (SOMs)

To quantify the energy-meteorology climatology of the Eastern Cape province, the approach of using SOMs is proposed. These maps are used to objectively identify the prevailing synoptic weather types occurring in the Eastern Cape Province of South Africa.

The field of climatology has widely adopted the use of SOMs, a machine-learning based approach to clustering, in recent years and was introduced to the field in 2002 (Van Doan et al., 2021). Kohonen originally developed SOMs (Kohonen et al., 1996) for data mining. SOMs discover patterns intrinsic to complicated input datasets and as a result can generate a cluster of simplified representations of the dataset, called nodes. The most important patterns of the input dataset are represented by the nodes (Van Doan et al., 2021). Synoptic weather typing is an original use of applying SOMs in climatology (Sheridan et al., 2011) as used in

several studies over South and southern Africa (Lennard et al., 2014, Pinto et al., 2015) and elsewhere (Hewitson et al., 2002, Hope, 2006, Sammon, 1969).

The algorithm used by a SOM iterates and gradually updates the makeup of the nodes in the data space until it results in a converged solution i.e., the “best” summarized representation of the input data. For each iteration, the algorithm chooses a random input vector and matches it to one of the nodes. The “winning” node is called the best matching unit (BMU) (Van Doan et al., 2021).

Training is then carried out by adjusting the BMU and its neighbours to become closer to the input vector. The learning rate and neighbourhood function are key inputs that govern the training task. Traditional SOMs use the Euclidean distance (ED) to search for the BMU, where the “closest” node to an input vector in terms of ED will be assigned as the BMU (Van Doan et al., 2021).

5.2.6.1 SOM Software

The SOMPAK © software package (Kohonen et al., 1996) is one of the earliest realisations of the SOM methodology. It contains all programs necessary for the correct application of the SOM algorithm to visualise and cluster the ERA5 geopotential dataset.

5.2.6.2 SOM Input Dataset

For the purposes of this study, the fifth generation of the European Centre for Medium-Range Weather Forecast’s Atmospheric Reanalysis dataset (ERA5) (Hersbach et al., 2020a, ECMWF, 2021) at six hourly and $\sim 0.28^\circ$ (TL639⁷) temporal and spatial resolution respectively has been used for the period 2010 to 2019 to correlate with the equivalent resolution wind resource and energy production data. ERA5 geopotential at 1000 hPa, converted to geopotential height by dividing with 9.81 m/s^2 is used as variable, to characterise the 6-hourly circulation patterns.

⁷ Spectral coefficients or Gaussian grids are the method in which ERA5 data is archived to provide a somewhat uniform spacing over the globe. The ERA5 high resolution (HRES) wind resource data are archived on a reduced Gaussian linear grid and in the case of this study, the name of the grid is TL639 (DTU, 2020).

The data covers the Earth on a ~ 30km grid and resolves the atmosphere using 137 levels from the surface up to a height of 80 km. ERA5 data is known to provide a realistic representation of African rainfall patterns (Engelbrecht, F. et al., 2022) and likely also of the underpinning circulation patterns.

The domain for which the geopotential dataset was extracted spans southern Africa (16°E to 34°E and 22°S to 35°S), with the relevant smaller Eastern Cape domain of interest contained within the larger domain. To provide a normalised input for the SOM software, so that the seasonal differences in geopotential height do not dominate the SOM-derived synoptic types, the spatial average of geopotential across the Eastern Cape domain was subtracted from the value at each ERA5 grid point. That is, the SOM is developed using the special anomalies of geopotential, following Engelbrecht et al., (2015).

5.3 Methodology

The proposed methodology that follows is carried out in three major steps namely:

1. Energy Yield Analysis:
 - Step 1: Meteorological Data Acquisition and Wind Resource Analysis
 - Step 2: WEF modelling
 - Step 3: Net AEP Energy Yield Analysis
 - Step 4: Daily Energy Production Calculation
2. SOM Training
3. Energy Mapping:
 - Step 1: Match energy production to each node
 - Step 2: Identifying the corresponding synoptic type for each of the 35 SOM nodes

5.3.1 Energy Yield Analysis

A crucial part of the energy yield analysis for a WEF is a sufficiently long period of observed wind resource timeseries, derived from measurement instruments mounted on a meteorological mast on the site. This observed wind resource data generally needs to be properly quality controlled to make sure there are no anomalies that could impact the energy production calculations.

Step 1: Meteorological Data Acquisition and Wind Resource Analysis:

The typical process, also applied here, is recommended as follows:

1. Confirmation that the duration of measurement is longer than 1 year. In this case, 10 years of measured data was available to use from the WASA meteorological masts. Note that the requirement of having data for at least 1 year is currently a general requirement of lenders and from a climatological perspective, a period of at least twenty years would have been preferred to fully characterise the inter-annual variability of weather systems.
2. Perform a visual inspection of the dataset to identify missing portions of data and remove severe outliers.
3. Make sure data availability is greater than 99% for the highest anemometers for the duration of the measurement period. If this is not achievable then other available anemometers can be used for data filling.
4. Verify all timestamps to make sure they are consecutive.
5. Data Quality Control:
 - a. Remove data that is greater than 18 days corrupted.
 - b. Replace data that is corrupted for less than 18 days and greater than 1 day from alternate instruments on the meteorological mast.
 - c. Repair values corrupted for less than 1 day by using data from a previous or subsequent day or take averages of the previous and following several days or fill data / extrapolate from another anemometer.
 - d. Perform a plausible value check to make sure the measured values are within reasonable limits.
 - e. Perform a plausible rate of change check to make sure that there are no unreasonable step changes in the data.

- f. Perform a tower shadow analysis to adjust measurements affected by the meteorological masts tower shadow.
- g. Perform a long-term adjustment using the closest node from a long-term reanalysis dataset such as ERA5 or MERRA2.

Similar methodologies have been employed by studies carried out globally and reinforce the use of reanalysis datasets for not only long-term correction but, where there is no measurement data, these datasets can be used as the base dataset in the quantification of the wind energy production, each of course having their unique strengths as outlined by Gruber et al., (Gruber et al., 2022). Some examples of such Wind Resource Assessment methodologies can be found from Oman and Thailand in (Khan et al., 2023) and (Charabi et al., 2019).

Step 2: WEF modelling:

The fundamental components that constitute the wind farm modelling software are outlined below, as well as the calculation procedures:

- a. An underlying Digital Terrain Model (DTM⁸).
- b. A preferred wind farm layout adhering to standard 3 rotor diameter (non-predominant wind direction) x 9 rotor diameter (predominant wind direction) WTG spacing to minimise internal WEF wake losses⁹.
- c. A suitable virtual WTG Model based on the Original Equipment Manufacturers (OEMs) power curve for the correct turbulence intensity, wind class and air density at the WTGs hub height.
- d. A virtual meteorological mast which is a virtual representation of the data derived from Step 1.
- e. A Wind Resource Grid (WRG) is derived from the Wind Atlas Analysis and Application Program (WASP) method of extrapolation (DTU, 2022) of the actual wind speeds at the met mast position to the actual WTG positions (DTU, 2020). The method of calculating the wind speeds at WTG hub height

⁸ The Digital Terrain Model associated with the wind farms modelled in this research contains an elevation layer derived from SRTM V.2 publicly available data, with 10 m contour height.

⁹ WEF Wake Losses: disturbance of the free wind speed by the WTG blades, in turn affecting the downstream wind turbines whereby the free wind speed loses some of its energy.

in the WAsP method makes use of a logarithmic wind profile¹⁰ dictated by the terrain surface roughness (DTU, 2020).

1. Once these items are in place, the wind farm modelling software, in some cases making use of Computational Fluid Dynamics (CFD) in extremely complex terrain, can build the wind flow model and calculate the AEP specific to the wind farm layout, WTG, DTM and observed wind resource data.
2. This AEP value is typically a Gross value with no losses deducted and is based on a Typical Meteorological Year (TMY) derived from the measurements and extrapolated to the WTG positions.

Step 3: Net AEP Energy Yield Analysis:

Considering a normal distribution, the P50 energy production is the centre value and is calculated as follows:

1. The wind energy modelling software calculates the wake losses for each WTG in a WEF and thereby the part-net annual energy production of each WTG turbine, and aggregates this for the entire WEF (CSIR, 2019).
2. Once the Gross AEP and the wake loss percentage are known, additional losses can be considered and factored into the final Net AEP. These are namely the 'Balance of Plant' (BOP) losses and are estimated based on experience and industry accepted norms, calculated where possible and taken from contractual turbine supply agreements. They are made up of the following items:
 - a. WTG availability (typically ~3%)
 - b. Electrical efficiency (typically ~2%)
 - c. WTG performance (typically ~3%)
 - d. Environmental (typically ~1%)
 - e. Curtailments (typically ~1%)
3. By applying all loss factors to the Gross AEP value, the net AEP can be calculated.

¹⁰ A logarithmic wind profile allows extrapolation of wind speeds measured at a particular height to the hub height of the WTG. The formula used is $U(z) = (u^*/K) \ln(z/z_0)$ where z is height from surface, z_0 is the roughness length, u^* is the friction velocity and K is the Von Karman constant.

4. Uncertainty: It should be noted that all the steps in such a methodology have inherent uncertainty particularly in the wind resource assessment and energy yield analysis. This can be calculated to determine probability values outside the P50, typically the P75 for lenders however, since we are concerned only with the P50 in this study, it is not within the scope. As an indication however, the overall Standard Deviation of the uncertainty associated with the sites covered in this study could range from 8 to 13%.

Step 4: Hourly energy production calculation:

1. The final step in the energy production process is to develop an '8760' energy production which is the annual energy at hourly resolution based on the average hourly wind speed for the wind farm for the 10-year period of interest (Frew et al., 2017).
2. Each hourly wind speed for the complete measured timeseries is passed through the WTG power curve to provide an energy production for each hour.
3. This is summed up for one year and compared to the Net AEP derived in step 3.
4. The average hourly windspeed values are then scaled to provide a matching Net AEP to that derived in step 3 thus intrinsically considering all the losses in the hourly average windspeed. This ensures that the WEF will still operate at or close to rated power for suitably high windspeeds.
5. The hourly energy production can then be adjusted to whatever resolution is required to correlate with the reanalysis data weather patterns, for example, 6-hourly data from ERA5.

5.3.2 SOM training

Based on the work done by Engelbrecht et al., (Engelbrecht, C. et al., 2014), who related Eastern Cape rainfall patterns to synoptic types using SOMs, it was decided to use 35 nodes (representing 35 characteristic synoptic type circulation patterns), derived from the ERA5 reanalysis dataset. The SOM was developed over the smaller Eastern Cape spatial area of interest (box in Figure 5-1).

SOMPAK © was used to produce the final trained SOM for this study using the following steps:

1. Data Preparation: SOMPAK © requires the data for input to be in a matrix 1 x N format prior to execution of the algorithm. To do this, a python script was used to reshape the 2-D ERA5 dataset into a 1-D matrix for input into the SOMPAK © software.
2. Running the SOMPAK © software: SOMPAK © creates the data files of common synoptic type patterns needed for producing the trained SOM map. Once the SOM has been trained using a vector quantization algorithm (Kohonen et al., 1996), i.e. the SOM with the 35 archetypical synoptic states is produced, it assigns a BMU for each timestep in the input dataset. The specifications used to run the software are as follows:
 - Lattice type: rectangular
 - Number of iterations: 100 000
 - Training is done in two phases 1) the ordering phase during which the reference vectors of the map units are ordered 2) the values of the reference vectors are fine-tuned
 - Initial neighbourhood radius: 3 (decreases to 1 during training)
 - Initial learning rate parameter: 0.1 (decreases to 0 during training)
3. It is necessary to confirm that the SOM result makes sense by checking the Sammon maps, a 2-d representation of the n-dimensional data space (Kohonen et al., 1996, Sammon, 1969). If there are folds in the map it is difficult to interpret implying that the radius of influence variable needs to be increased.

5.3.3 Energy mapping

Following the process of characterising the 35 synoptic types, the resultant energy production associated for each can be quantified via an energy mapping process as follows:

Step 1: Match energy production to each node:

1. SOMPAK © makes use of Euclidean distance to determine the BMU for each timestamp in the 10-year ERA5 dataset. In this way each timestep is mapped to a node.
2. It is then possible to map the energy produced in each correlated time step (sum of energy over the six-hour period) to the corresponding SOM node or BMU.
3. The corresponding energy production per timestep is then used to determine the best performing SOM node in terms of energy production.

Step 2: Identifying the corresponding synoptic type for each of the 35 SOM nodes:

1. The Eastern Cape Domain is too small to identify large scale drivers of the regional climate, so the timestamps associated with each node are used to extract the equivalent ERA5 geopotential (spatially normalized) timestamps for a larger spatial area including all South Africa.
2. This was then averaged per SOM node for the whole of South Africa to produce a single representative image of the synoptic type.
3. These can then be compared to commonly occurring synoptic weather types and assigned to the one that matches it the best.

5.4 Results and Discussion

5.4.1 Wind resource

In summary, each of the four WEF sites have a capacity between 148.5 MW and 192.5 MW and employ 3-Bladed, 155 m diameter, horizontal axis, 5.5 MW WTGs at 120 m AGL hub height.

The table below provides the mean wind speeds of the four wind farm sites amongst other characteristics. The mean wind speeds are typical of a class III wind site as per the IEC wind classification. This implies a good wind resource and power density.

WEF WM09, situated in the North of the EC Province, sees the highest average annual wind speeds with the other three WEFs - WM07 (Eastern EC), WM08 (Southern EC), WM10 (Western EC) – also showing similar profiles. Wind shears tend to be quite different per site with WM07 showing the highest wind shear i.e. the increase in wind speed with increased height. Finally, the wind speed frequency distributions k parameter shows WM09 and WM07 have values close to 3 implying relatively stable wind speeds whereas the other two show moderately stable wind speeds. This is corroborated by the relatively low turbulence intensity values.

Table 5-2: Annual site wind resource characteristics at met mast height

	WM07	WM08	WM09	WM10
	WEF	WEF	WEF	WEF
	(62m)	(62m)	(62m)	(62m)
Annual Mean Wind Speed-U (m/s)	6.95	7.22	8.00	6.65
Wind Shear Exponent (α)	0.163	0.160	0.136	0.137
Weibull k parameter	2.37	2.05	2.34	2.02
Turbulence Intensity	0.12	0.12	0.11	0.12
Power Density @ 50 m (W/m²)	268	388	392	278

Table 5-3 summarizes the general annual, seasonal, and diurnal site characteristics for each modelled WEFs meteorological mast data. At all four of the sites, the annual average wind speeds, which vary between 7 and 8 m/s, confirm the favourable wind potential that exists across the Eastern Cape. At three of the four sites, most months exhibit the strongest winds around midday (Table 5-3). This is likely the consequence of the land-sea temperature gradient being at its strongest around midday, which contributes to enhanced pressure-gradients and high wind speeds. The exception is site WM07, where most months exhibit the strongest wind speeds at night.

At sites WM09 and WM10, average monthly wind speeds peak in winter, and remain relatively high in summer. Closer to the coast at site WM08, wind speeds peak in spring and summer but remain relatively high in autumn and winter. At

site WM07 over the western interior, autumn and spring are seasons with high wind speeds at night, but with winter recording high values on the average right through the diurnal cycle.

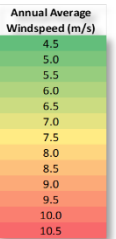
Table 5-3: 12 x 24 – Monthly and Diurnal Site wind resource characteristics

WM07 WEF

Hour	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	All
00:00-01	8.621	8.222	7.881	7.54	7.105	7.583	7.597	7.698	7.8	7.961	8.248	8.3	7.873
01:00-02	8.092	7.821	7.513	7.367	7.041	7.595	7.592	7.487	7.64	7.708	7.89	7.774	7.624
02:00-03	7.564	7.437	7.07	7.111	6.944	7.056	7.384	7.365	7.412	7.487	7.639	7.363	7.372
03:00-04	7.189	7.035	6.769	6.789	6.736	7.55	7.298	7.191	7.201	7.253	7.356	7.164	7.132
04:00-05	6.941	6.704	6.424	6.588	6.608	7.371	7.121	7.08	7.048	6.954	7.001	6.932	6.903
05:00-06	6.666	6.472	6.285	6.431	6.418	7.294	6.969	7.095	6.88	6.795	6.74	6.676	6.734
06:00-07	6.196	6.216	6.134	6.274	6.323	7.138	6.93	6.905	6.703	6.477	6.272	6.181	6.489
07:00-08	5.855	5.737	5.721	6.117	6.294	7.047	6.924	6.709	6.35	6.051	5.99	5.978	6.245
08:00-09	5.495	5.435	5.255	5.617	5.992	6.994	6.743	6.2	6.002	5.9	5.685	5.694	5.935
09:00-10	5.148	5.19	5.136	5.528	5.593	6.488	6.164	6.091	5.967	5.903	5.467	5.359	5.69
10:00-11	5.041	4.985	5.039	5.831	5.869	6.829	6.418	6.528	5.926	5.92	5.446	5.242	5.773
11:00-12	5.043	4.98	5.192	5.831	6.157	7.19	6.851	6.892	6.199	6.152	5.549	5.396	5.975
12:00-13	5.274	5.095	5.462	6.009	6.308	7.335	7.181	7.124	6.534	6.309	5.812	5.604	6.194
13:00-14	5.561	5.461	5.687	6.143	6.489	7.493	7.316	7.173	6.746	6.463	6.194	5.813	6.398
14:00-15	5.967	5.766	5.924	6.263	6.444	7.506	7.282	7.315	6.876	6.707	6.545	6.095	6.574
15:00-16	6.34	6.094	6.201	6.268	6.367	7.427	7.064	7.248	6.904	7.01	6.956	6.549	6.713
16:00-17	6.87	6.575	6.466	6.162	6.208	6.989	6.724	7.05	7.039	7.251	7.49	7.051	6.824
17:00-18	7.509	7.107	6.864	6.28	5.943	6.489	6.41	6.893	7.18	7.599	8.001	7.927	7.006
18:00-19	8.463	7.715	7.463	6.496	5.944	6.532	6.366	6.899	7.315	7.968	8.494	8.613	7.338
19:00-20	9.269	8.495	7.885	6.823	6.242	6.946	6.618	7.175	7.486	8.41	8.937	9.242	7.654
20:00-21	9.525	8.809	7.946	7.177	6.544	7.138	6.934	7.422	7.73	8.754	9.014	9.401	8.012
21:00-22	9.563	8.756	8.03	7.398	6.829	7.43	7.238	7.672	7.947	8.845	8.983	9.367	8.154
22:00-23	9.454	8.741	8.099	7.591	7.013	7.562	7.417	7.69	7.97	8.616	8.873	9.149	8.167
23:00-24	9.052	8.462	8.13	7.574	7.232	7.592	7.538	7.772	7.933	8.339	8.569	8.835	8.075

WM08 WEF

Hour	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	All
00:00-01:00	6.128	5.921	6.534	6.549	6.285	7.24	7.209	7.063	7.045	6.792	6.59	6.035	6.601
01:00-02:00	6.087	6.118	6.338	6.382	6.172	7.337	7.239	7.275	7.12	6.792	6.574	6.121	6.612
02:00-03:00	6.049	6.126	6.383	6.366	6.173	7.337	7.213	7.104	7.107	6.953	6.635	6.112	6.606
03:00-04:00	5.969	6.055	6.403	6.33	6.323	7.308	7.34	7.015	7.214	6.938	6.662	6.109	6.622
04:00-05:00	6.025	6.047	6.403	6.281	6.323	7.428	7.356	6.952	7.254	6.809	6.78	5.94	6.614
05:00-06:00	6.023	5.917	6.395	6.223	6.288	7.472	7.371	6.897	7.306	6.824	6.678	5.988	6.588
06:00-07:00	5.909	5.98	6.397	6.262	6.346	7.504	7.358	6.958	7.274	6.812	6.659	5.776	6.582
07:00-08:00	5.891	6.002	6.238	6.145	6.406	7.405	7.372	6.92	7.277	6.785	6.79	6.005	6.582
08:00-09:00	6.507	6.461	6.271	5.945	6.416	7.371	7.34	6.83	7.344	7.119	7.431	6.672	6.798
09:00-10:00	6.975	7.19	6.807	6.287	6.251	7.29	7.188	6.87	7.676	7.736	7.959	7.229	7.126
10:00-11:00	7.391	7.652	7.249	6.78	6.624	7.575	7.404	7.351	8.105	8.19	8.442	7.706	7.548
11:00-12:00	7.939	8.15	7.665	7.081	7.012	7.997	7.553	7.752	8.497	8.598	8.812	8.164	7.947
12:00-13:00	8.449	8.619	8.181	7.445	7.334	8.252	7.84	7.947	8.767	8.973	9.21	8.539	8.313
13:00-14:00	8.91	8.842	8.515	7.66	7.462	8.322	8.022	8.041	8.984	9.213	9.406	8.74	8.53
14:00-15:00	9.153	8.975	8.645	7.77	7.533	8.053	7.959	8.087	9.08	9.118	9.345	8.832	8.57
15:00-16:00	9.199	8.866	8.673	7.694	7.339	7.842	7.718	7.958	8.945	9.072	9.262	8.938	8.489
16:00-17:00	9.105	8.597	8.505	7.495	6.982	7.454	7.42	7.745	8.461	8.738	9.101	8.947	8.238
17:00-18:00	8.805	8.216	7.975	7.09	6.577	7.078	7.109	7.179	7.875	8.325	8.663	8.585	7.823
18:00-19:00	8.268	7.626	7.319	6.672	6.386	7.057	6.802	6.967	7.334	7.691	7.981	8.093	7.373
19:00-20:00	7.488	7.028	6.757	6.768	6.278	7.072	6.619	6.998	7.108	7.206	7.317	7.455	7.02
20:00-21:00	6.814	6.565	6.508	6.735	6.326	6.95	6.725	7.028	6.95	7.001	7.038	6.947	6.801
21:00-22:00	6.561	6.481	6.475	6.618	6.378	7.156	6.856	7.006	6.783	6.993	6.774	6.551	6.708
22:00-23:00	6.304	6.286	6.436	6.573	6.342	7.13	6.934	6.973	6.886	6.969	6.6	6.338	6.639
23:00-24:00	6.175	6.031	6.467	6.523	6.269	7.144	6.996	6.982	6.854	6.871	6.635	6.252	6.59



WM09 WEF

Hour	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	All
00:00-01	7.574	7.161	7.004	6.84	7.776	9.437	8.434	8.187	7.458	7.45	7.543	7.586	7.7
01:00-02	7.219	6.88	6.807	6.754	7.812	9.441	8.447	8.3	7.535	7.39	7.289	7.262	7.588
02:00-03	7.03	6.629	6.72	6.801	7.74	9.628	8.543	8.376	7.594	7.37	7.19	6.94	7.538
03:00-04	6.384	6.501	6.728	6.921	7.798	9.784	8.45	8.258	7.663	7.306	7.271	6.889	7.547
04:00-05	6.805	6.385	6.606	7.021	7.91	9.789	8.732	8.264	7.717	7.3	7.141	6.831	7.535
05:00-06	6.911	6.444	6.702	7.073	7.849	9.555	8.772	8.357	7.804	7.377	7.13	6.752	7.552
06:00-07	6.831	6.547	6.863	7.147	7.975	9.582	8.708	8.463	7.93	7.389	6.999	6.489	7.569
07:00-08	6.456	6.417	6.817	7.129	7.98	9.608	8.776	8.542	7.904	7.228	6.91	6.319	7.496
08:00-09	6.391	6.309	6.662	6.968	7.807	9.607	8.639	8.402	7.696	7.306	7.032	6.478	7.43
09:00-10	6.539	6.464	6.818	7.018	7.613	9.224	8.558	8.426	8.026	7.642	7.299	6.803	7.52
10:00-11	6.627	6.73	7.052	7.326	7.822	9.372	8.763	8.777	8.541	7.973	7.786	7.205	7.81
11:00-12	6.68	6.998	7.392	7.622	8.257	9.738	9.095	9.298	9.002	8.371	8.182	7.538	8.156
12:00-13	6.771	7.142	7.685	7.803	8.7	10.051	9.408	9.602	9.374	8.541	8.478	7.821	8.422
13:00-14	7.034	7.103	7.883	7.911	8.975	10.153	9.522	10.045	9.626	8.662	8.681	8.131	8.617
14:00-15	7.172	7.202	7.905	7.935	8.978	10.013	9.436	10.205	9.669	8.722	8.8	8.36	8.673
15:00-16	7.292	7.139	7.82	7.904	8.45	9.783	9.251	10.062	9.575	8.703	8.943	8.499	8.617
16:00-17	7.649	7.324	7.772	7.834	8.612	9.526	8.925	9.759	9.483	8.637	8.893	8.744	8.573
17:00-18	7.788	7.429	7.543	7.694	8.139	9.15	8.645	9.217	9.124	8.682	8.942	8.761	8.404
18:00-19	8.163	7.556	7.469	7.465	7.798	8.981	8.413	8.71	8.665	8.672	9.079	8.723	8.291
19:00-20	8.466	7.769	7.405	7.266	7.587	9.05	8.438	8.514	8.258	8.616	8.939	8.907	8.254
20:00-21	8.497	7.869	7.563	7.242	7.58	9.089	8.389	8.319	7.995	8.49	8.844	8.909	8.239
21:00-22	8.516	7.898	7.527	7.009	7.665	9.167	8.276	8.156	7.876	8.214	8.752	8.813	8.15
22:00-23	8.292	7.711	7.22	6.924	7.808	9.362	8.145	8.121	7.779	7.901	8.394	8.343	7.996
23:00-24	7.876	7.362	7.056	6.852	7.835	9.388	8.211	8.256	7.657	7.618	7.944	7.844	7.82

WM10 WEF

Hour	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	All
00:00-01	5.975	5.66	5.725	5.809	5.97	7.254	7.02	6.847	6.203	6.23	6.122	5.936	6.226
01:00-02	5.834	5.602	5.675	5.794	6.125	7.264	6.838	6.857	6.205	6.004	6.018	5.697	6.154
02:00-03	5.54	5.347	5.508	5.641	6.085	7.491	6.898	6.784	6.122	5.947	5.948	5.679	6.076
03:00-04	5.337	5.136	5.309	5.571	6.023	7.563	6.832	6.734	5.885	5.863	5.717	5.505	5.965
04:00-05	5.213	5.083	5.099	5.579	6.022	7.662	6.798	6.662	5.896	5.62	5.641	5.407	5.882
05:00-06	5.194	5.013	4.987	5.535	6.237	7.682	6.915	6.685	5.857	5.713	5.604	5.2	5.874
06:00-07	5.085	4.955	4.905	5.469	6.219	7.767	7.054	6.758	6.036	5.536	5.488	5.183	5.851
07:00-08	5.066	4.881	4.891	5.456	6.276	7.776	7.276	6.602	6.086	5.565	5.495	5.163	5.851
08:00-09	5.21	4.991	5.058	5.446	6.277	7.776	7.276	6.602	6.086	5.565	5.495	5.163	5.851
09:00-10	5.327	5.182	5.34	5.687	6.347	7.610	6.999	7.232	6.604	6.105	5.917	5.453	6.185
10:00-11	5.494	5.375	5.544	6.009	6.736	8.761	7.646	7.678	6.919	6.497	5.921	5.551	6.498
11:00-12	5.679	5.628	5.618	6.149	7.004	9.163	8.146	8.095	7.078	6.299	6.642	5.739	7.641
12:00-13	5.702	5.702	5.702	6.149	7.004	9.163	8.146	8.095	7.078	6.299	6.642	5.739	7.641
13:00-14	5.687	6.045	5.888	6.305	7.054	9.053	8.298	8.112	7.39	7.083	7.041	7.224	7.224
14:00-15	7.634	6.68	6.31	6.383	6.791	8.884	8.08	8.147	7.784	7.628	8.242	7.947	7.558
15:00-16	8.29	7.391	6.915	6.633	6.702	8.369	7.78	8.197	8.164	8.289	8.772	8.64	7.888
16:00-17	8.659	7.895	7.306	6.633	6.489	7.874	7.475	8.176	8.493	8.581	8.963	7.972	7.558
17:00-18	8.659	7.895	7.306	6.633	6.489	7.874	7.475	8.176	8.493	8.581	8.963	7.972	7.558
18:00-19	8.659	7.895	7.306	6.633	6.489	7.874	7.475	8.176	8.493	8.581	8.963	7.972	7.558
19:00-20	8.659	7.895	7.306	6.633	6.489	7.874	7.475	8.176	8.493	8.581	8.963	7.972	7.558
20:00-21	7.846	7.521	7.128	6.421	5.858	7.031	7.032	7.2	7.319	5.97	7.615	7.626	7.192
21:00-22	7.198	7.004	6.644	6.084	5.756	6.687	6.651	6.841	6.685	7.003	7.01	7.113	6.732
22:00-23	6.81	6.408	6.12	5.796	5.873	6.969	6.399	6.728	6.352	6.792	6.65	6.615	6.493
23:00-24	6.525	6.052	6.084	5.796	5.873	6.969	6.399	6.728	6.352	6.792	6.65	6.615	6.493
24:00-24	6.278	5.722	5.788	5.728	6.113	7.005	6.789	6.522	6.045	6.382	6.249	6.036	6.438

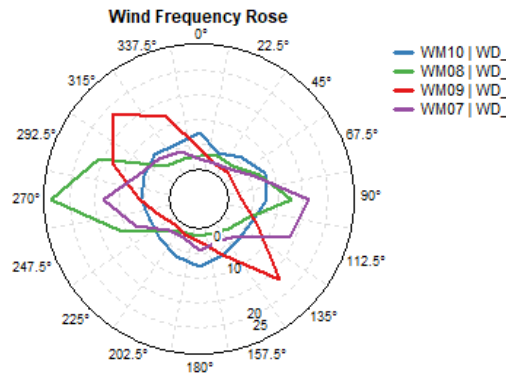


Figure 5-3: Wind roses showing predominant wind direction for all Eastern Cape WEF sites

5.4.2 Energy yield analysis

The P50 AEP per site is consistent with the wind resource assessment results provided (Table 5-2). WM09 (41.5% and 42.1%) and WM08 (41.6% and 42.0%) are providing the highest energy production figures and net capacity factors (NCFs) from WASP © and Openwind © respectively (Figure 5-4). WM10 (37.2% and 37.4%) and WM07 (41.8% and 41.3%) WEF sites are modelled to produce somewhat less energy. In general, the WASP © and Openwind © versions of the models are producing energy production results that are very similar and differ by no more than 1.5%.

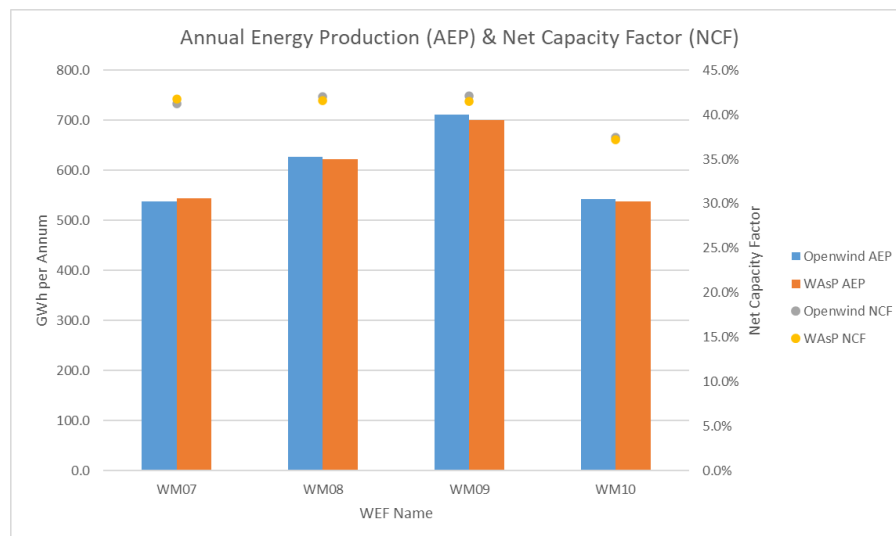


Figure 5-4: P50 Annual Net energy production and Net Capacity Factor per WEF from Openwind © and WASP ©

The P50 monthly energy production per site (Figure 5-5) shows WM09 providing the highest energy production across the four sites, particularly so in the winter months. The WEF sites generally show higher production in the winter months at WM07, WM09 and WM10. At site WM08, the near coast location, the highest production is simulated for spring.

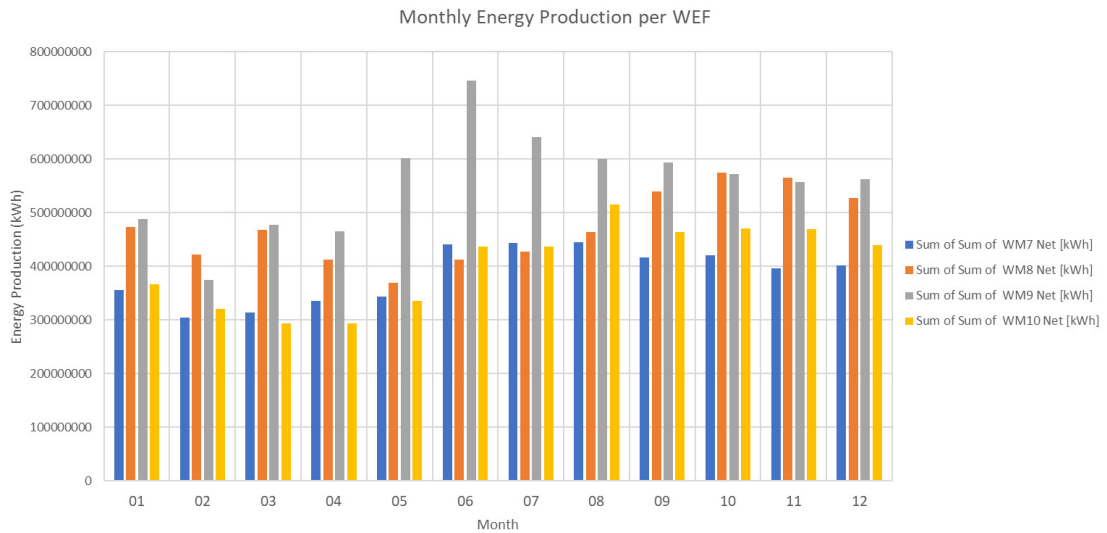


Figure 5-5: P50 Monthly energy production per modelled WEF site

5.4.3 SOM Results

Following Engelbrecht et al. (2015), a 35 node SOM has been developed to characterise the low-level synoptic circulation types of the Eastern Cape domain (Figure 5-6) using 1000 hPa geopotential height anomalies.

To obtain a more extensive spatial view of these systems, the same BMUs used to construct Figure 5-6 were applied to construct the relevant circulation patterns over a larger spatial domain (Figure 5-7), to obtain better insight into the spatial characteristics, and better identify the synoptic type associated for each of the SOM nodes shown in Figure 5-6.

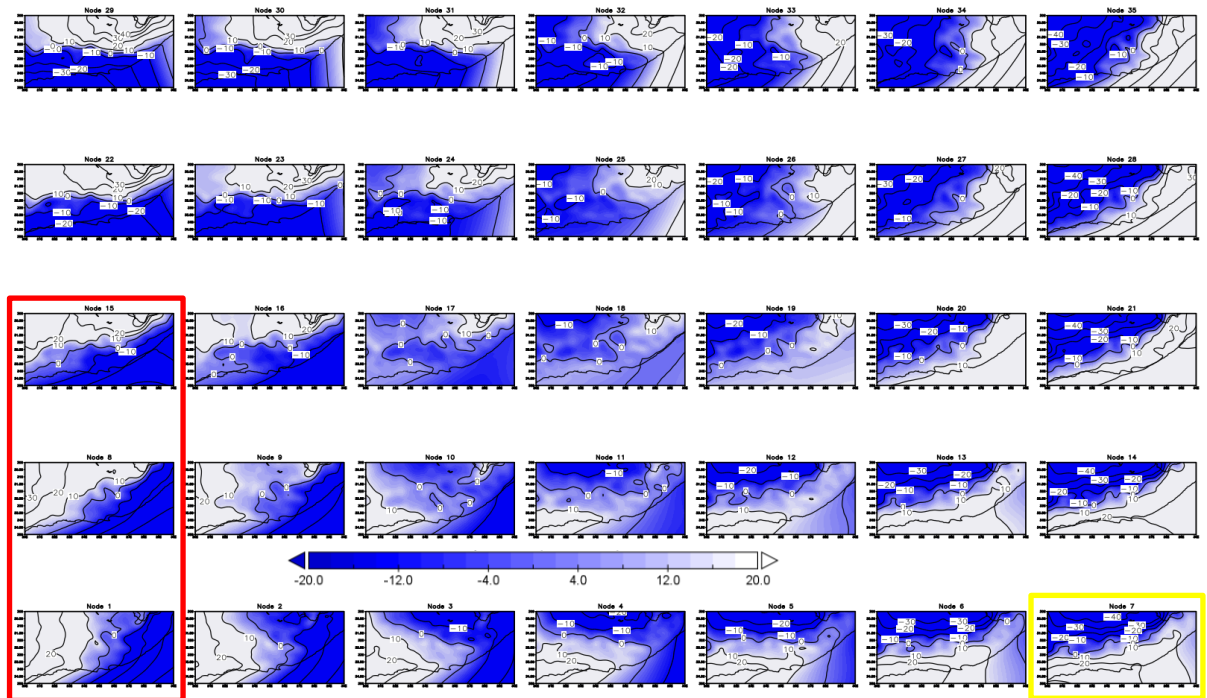


Figure 5-6:35-node SOM for geopotential height anomalies in metres (Red = Top 3 energy producing nodes, Yellow = lowest energy producing node) representing 35 low-level circulation types for the Eastern Cape (20° to 30°E; -30° to -35°S).

The top-left corner-node of the SOM (node 29, Figure 5-6) show negative geopotential anomalies to the south of the Eastern Cape, and over the southern part of the Eastern Cape, with positive anomalies over the northern interior. This pattern is due to a mid-latitude cyclone approaching from the west (Figure 5-7). The bottom-right corner of the SOM (node 7, Figure 5-7) shows the ‘opposite pattern’, positive geopotential anomalies south of and over the southern Eastern Cape, with negative anomalies over the northern interior. This pattern is the consequence of the Atlantic Ocean High starting to ridge along the Cape south coast (Figure 5-7). The bottom-left corner of the SOM (node 1, Figure 5-6) shows positive geopotential anomalies over the western part of the domain, with negative anomalies to the east. This is due to the Atlantic Ocean High ridging behind a steep trough and cold front (Figure 5-7). The ‘opposite’ pattern appears in the top-right corner of the SOM (node 35, Figure 5-6). It is the result of the Atlantic Ocean High ridging further to the east over the South African east coast, with a deep surface trough present over the western interior regions of South Africa.

Because each 6-hourly circulation pattern occurring in the ten-year period is associated with one of the SOM nodes, the energy production of that 6-hour period can be mapped onto the relevant node for each of the WEF sites. In this way it is possible to calculate the energy production associated with each node (Figure 5-8 and Figure 5-10). When ranking the energy production across nodes using Figure 5-8 and Figure 5-10, SOM nodes 8, 15, 1 (red outline, Figure 5-6, Figure 5-7, Figure 5-8) show the largest potential for energy production. All three of these nodes are characteristic of various stages of a deep mid-latitude cyclone passing to the south of the Eastern Cape, with the Atlantic Ocean High ridging behind the cold front over the Eastern Cape.

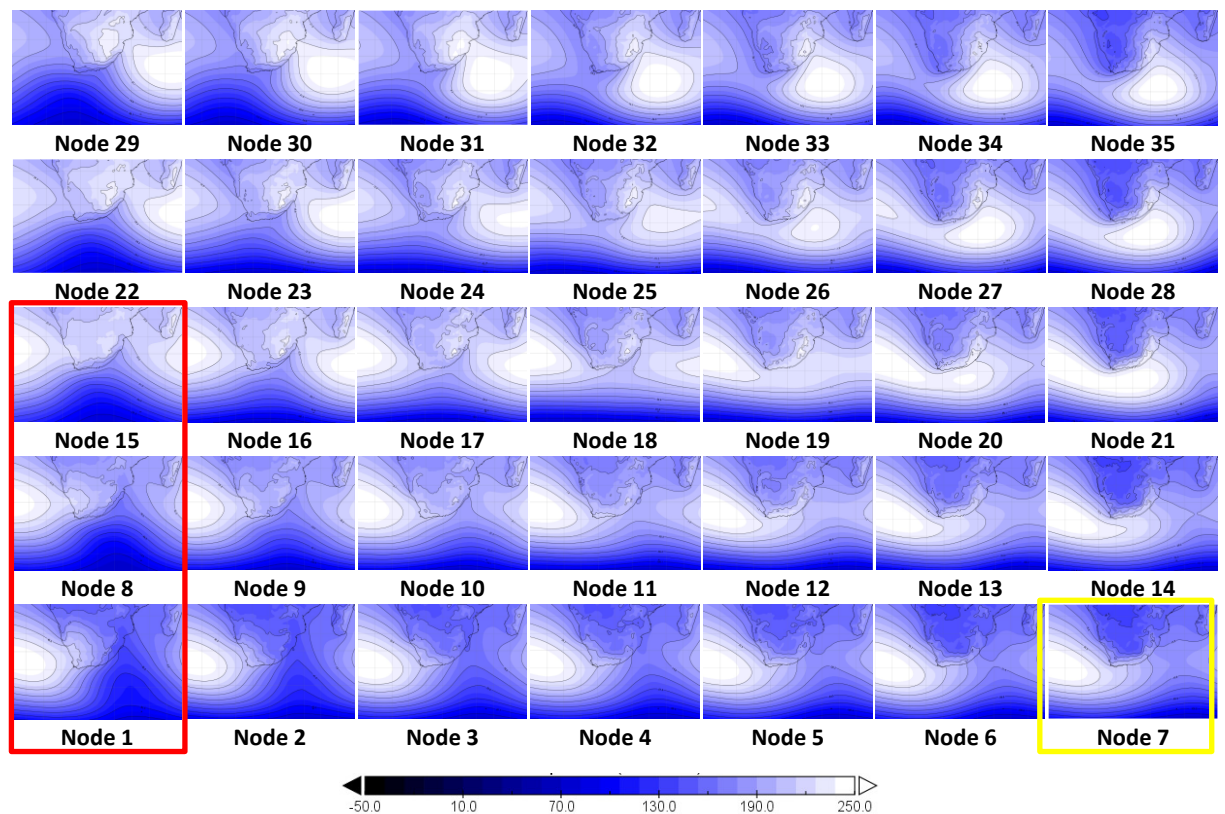


Figure 5-7: Accompanying synoptic pattern (geopotential height anomalies in metres) per SOM node (0° to 50°E; -10° to -50°S)

To explore in more detail (Figure 5-8) the seasonality of energy production in the Eastern Cape, the monthly energy production per node is shown (January to February, JFM, row 1; April to June, AMJ, row 2; June to September, JAS, row 3, October to December, OND, row 4). From this analysis the three nodes with the highest energy potential contribute most to annual production during the

winter months (June to August). This is not surprising, given that these nodes are associated with the passage of cold fronts over the Eastern Cape that occur in association with steep pressure gradients caused by the Atlantic Ocean High (Figure 5-6, Figure 5-7).

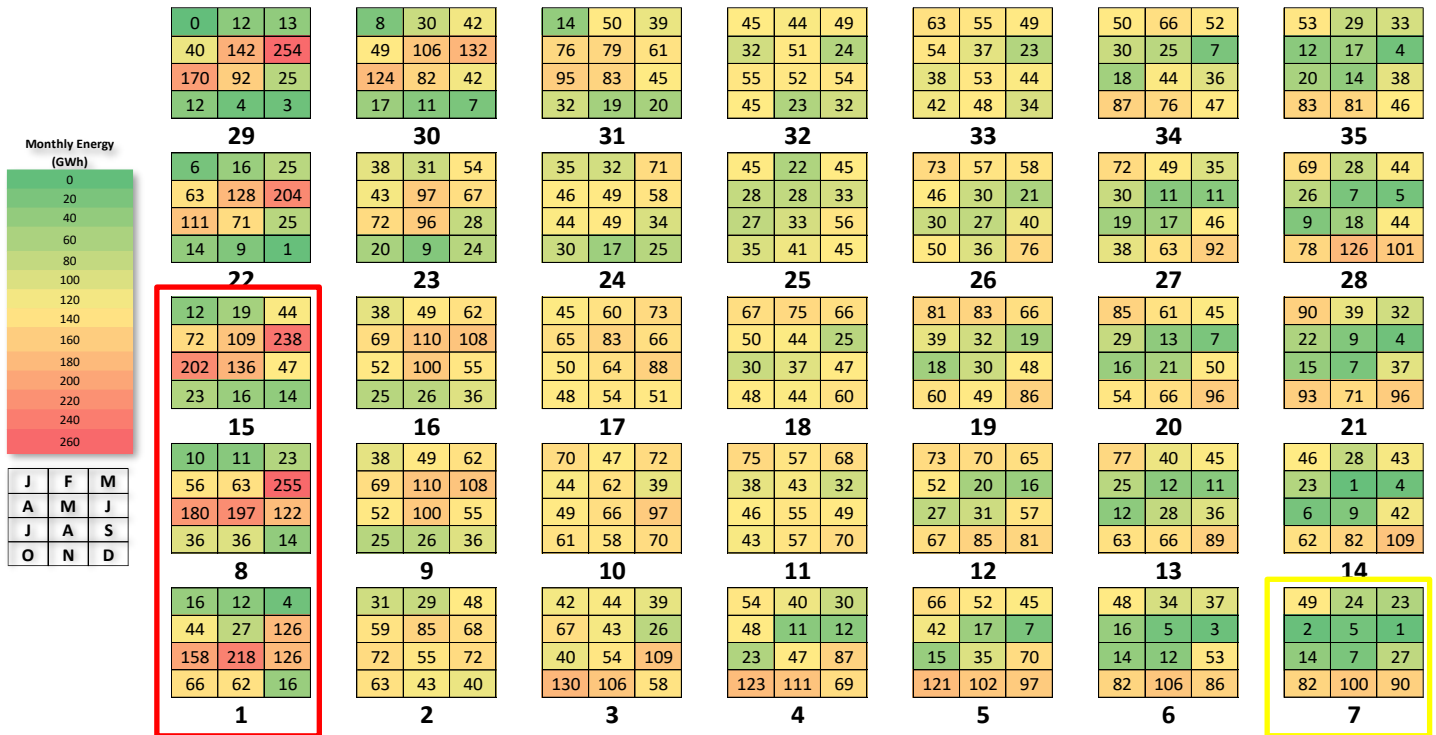


Figure 5-8: Monthly Total Energy Distribution per Node summed for all four WEF sites (GWh)

Figure 5-9 shows the average wind speed direction per trained SOM node (averaged across the Eastern Cape domain). Consistent with the wind rose calculated for each of the sites (Figure 5-3), the analysis shows the importance of predominantly westerly and easterly wind components for wind energy production in the Eastern Cape. The nodes associated with the highest energy production (marked in red, nodes 8, 15, and 1) have wind directions of $\sim 225^\circ$, consistent with the marked pressure gradients when the Atlantic Ocean High ridges behind a cold front. For all these cases the Atlantic High's centre is at 30°S or further to the north (Figure 5-11a to c), which is indicative of the importance of northward displaced synoptic-scale circulation patterns for optimal wind energy production in the Eastern Cape.

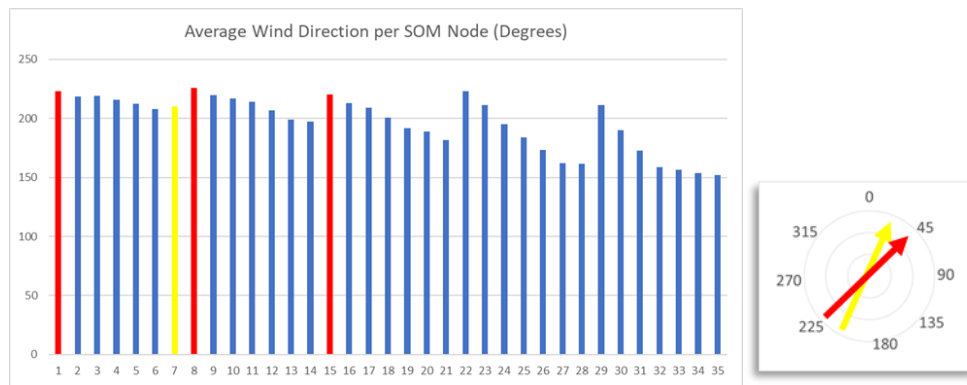


Figure 5-9: Average wind direction in degrees from North per trained SOM node

The annual frequency distribution map of SOM nodes is shown in Figure 5-10. The SOM methodology functions in such a way that the distribution of constituting cases per node is relatively uniform across nodes. Figure 5-10 also indicates the average energy production per day per node which provides a reasonable proxy by which to compare the strength of each node to provide wind energy (again noting high energy producing nodes 1, 8, and 15).

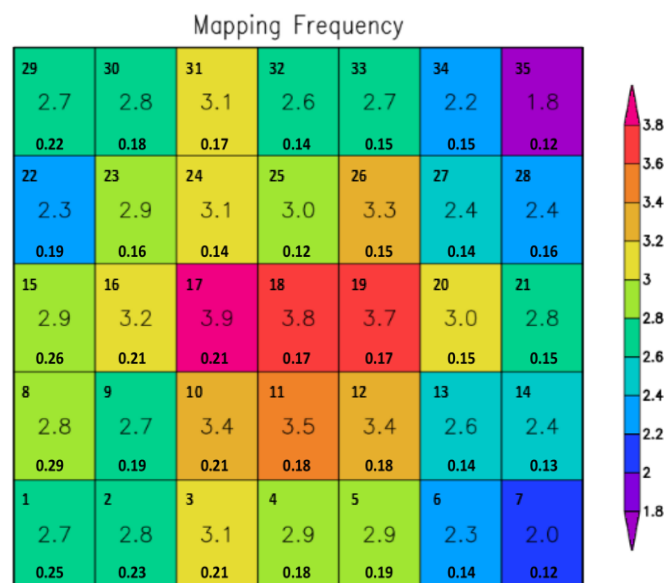


Figure 5-10: Trained SOM node annual frequency map (including energy in GWh/day below each frequency), node number in top right corner.

5.4.4 Highest wind energy production nodes

To gain further qualitative insights into the energy meteorology of the Eastern Cape, we explore the synoptic patterns (Figure 5-7Figure 5-6) associated with

the best and worst energy producing Eastern Cape circulation types (Figure 5-6) in more detail in Figure 5-11.

The patterns displayed for the top three energy producing circulation types (nodes 8, 15, and 1, Figure 5-11 a-c), as noted before, are indicative of the Atlantic Ocean High with a centre near 30 °S ridging behind a cold front and an associated mid-latitude cyclone passing to the south of the country. For all three cases, the net result is pronounced southwesterly flow over the Eastern Cape, parallel to the geopotential height contours, and reinforcing the importance of strong southwesterlies for wind energy generation in the Eastern Cape.

A similar study is carried out by Cheneka et al. 2021 and investigates the impact of various weather systems on the Belgian offshore wind fleet energy production using SOMs. In it's conclusion, the high wind energy producing SOM nodes display similar characteristics to those identified in this study i.e., they are characterised by low pressure systems in front of ridging high-pressure systems similar to the mid-latitude cyclones observed in South Africa (Cheneka et al., 2021).

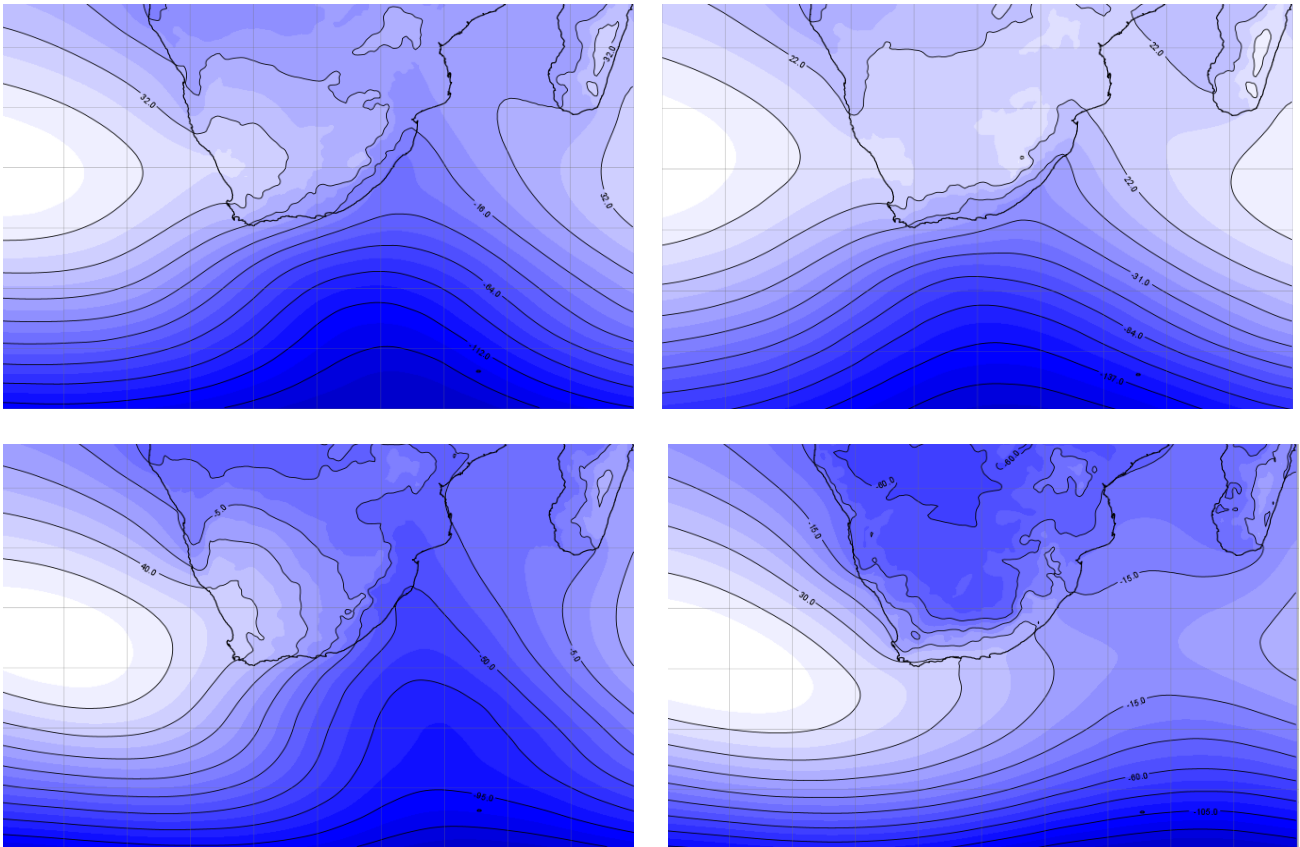


Figure 5-11 a) Trained SOM Node 8 b) 15 c) 1 d) 7 inset above the greater synoptic pattern 0° to 50°E; - 10° to -50°S (Geopotential height in metres reduced by spatial average of geographical focus area)

The circulation type and associated synoptic pattern that has the lowest energy generation potential for the Eastern Cape, node 7 (Figure 5-11d), represents mid-latitude cyclones with a more poleward location and a weak ridging high pressure with centre at about 35°S. Pressure gradients are consequently weak over the Eastern Cape, and wind energy production is low.

5.5 Conclusion

For South Africa to pursue a Just Energy Transition out of its heavy dependence on coal, it needs to increasingly invest in the country's rich resources in wind and solar energy. The Eastern Cape province has a very high potential for wind energy production and in this thesis, we explore the relevant energy meteorology and its seasonality in more detail.

The foundation for the study is the long-term meteorological wind mast measurement data available from WASA for four sites in the Eastern Cape, which enabled the calculation of annual and seasonal energy production at four representative locations, in the Eastern Cape. For these energy yield analyses realistic WEF and WTG designs at each of the four sites are used and run using different software to derive the wind energy production results. The four sites provide good coverage and are representative of the spatial areas energy production potential.

At each of the four sites, annual average wind speeds vary between 7 and 8 m/s, indicating a potentially high wind resource. The energy yield analysis reveals the importance of winter as the season with the highest energy potential. This is not a surprising result, given the northward passage of mid-latitude cyclones over the Southern Ocean in winter. Generally, energy production is the highest around midday and the afternoon, likely because the ocean temperature gradient is then at its steepest, strengthening the pressure gradients and winds.

Following the energy yield analysis, a 35 node SOM was generated to identify the prevailing circulation types of the Eastern Cape, using ERA5 reanalysis data at 6-hourly resolution. This SOM result is then mapped onto the six-hourly P50 energy production. Van Aarde et al., in 2023 follows a similar methodology for South Africa, focusing on resource potential (van Aarde et al., 2023) without taking the next step of providing detailed energy modelling methodologies and results. This study is hereby the first to quantify the energy meteorology of the Eastern Cape, by objectively exploring the detailed P50 energy production of different synoptic types.

The SOM analysis reveals that the synoptic-circulation pattern with the highest energy potential for the Eastern Cape is the Atlantic Ocean ridging high with its centre at about 30 °S, behind a northward displaced mid-latitude cyclone. This results in steep pressure gradients and predominantly south-westerly winds over the Eastern Cape. However, when mid-latitude cyclones pass over the Southern Ocean further to the south, and the Atlantic Ocean High ridges with its centre further to the south at about 35 °S, pressure gradients and energy production is weakest.

SOM nodes 8, 15, 1 (red outline, Figure 5-6, Figure 5-7, Figure 5-8) show the largest potential for energy production. All three of these nodes are characteristic of various stages of a deep mid-latitude cyclone passing to the south of the Eastern Cape, with the Atlantic Ocean High ridging behind the cold front over the Eastern Cape. These three nodes with the highest energy potential contribute most to annual production during the winter months (June to August) and have predominant wind directions of ~ 225°, consistent with the marked pressure gradients when the Atlantic Ocean High ridges behind a cold front.

The methodology developed here, linking energy production at WEF sites to archetypal synoptic types identified by the SOM, provides the foundation for the prediction of wind energy production at various timescales. Particularly, for seasonal forecasts and climate change projections using GCMs whose spatial resolution is relatively low.

This method can be applied to an ensemble of GCMs to project future energy potential through the lens of projected changes in synoptic type frequencies. These changes, in combination with the energy potential associated with the different synoptic types, will effectively yield predictions of future wind energy production. Applications could include improved understanding of the long-term viability of wind farm sites, guidance on renewable energy development zones, technology selection and integrated resource planning.

5.6 Author contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Greg Landwehr, and supported by Francois Engelbrecht and Chris Lennard. The first draft of the manuscript was written by Greg Landwehr and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

5.7 Declarations

5.7.1 Funding

Funding: This work was supported by the National Research Foundation of South Africa through its Earth System Science Research Programme, Grant 118598.

5.7.2 Conflict of interest statement

All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

5.7.3 Data availability statement

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

CHAPTER 6: PAPER 2 - Projected changes in the wind energy potential of South Africa’s Eastern Cape Province under climate change

Re-submitted to the International Journal of Climatology

Impact Factor 3.6

Date Submitted: 7 October 2024

Submission ID: JOC-24-0683

Contributions:

Gregory Landwehr (80%)	Francois Engelbrecht (12%)	Chris Lennard (8%)
• Conceptualization • Data curation • Formal analysis • Investigation • Methodology • Project administration • Writing - original draft • Writing - review & editing	• Conceptualization • Funding acquisition • Methodology • Project administration • Supervision • Writing - review & editing	• Conceptualization • Methodology • Supervision • Writing - review & editing

6. Paper 2 (Chapter 6) in the context of Paper 1 (Chapter 5) and Paper 3 (Chapter 7)

Results from Paper 1 (Chapter 5) are now used in Paper 2 (Chapter 6) towards obtaining projections that demonstrate the future changes in wind energy production under various climate change mitigation scenarios. Paper 2 (Chapter 6) follows the approach of using CMIP6 GCM projections which simulate future climate change towards quantifying long term fluctuations in synoptic weather type frequency and hence, wind energy production over the Eastern Cape.

Possible commercial impact on types and sizes of WEFs aligned with what is common in the REIPPPP latest bidding rounds are then investigated for the WEF lifetime and in the long term.

The methodology and results from Paper 1 (Chapter 5) and Paper 2 (Chapter 6) are then used as the platform on which to base climate risk mitigation measures for WEFs.

Abstract

South Africa transitioning to renewable and sustainable energy is a possibility if steps are taken to achieve this (RSA Government, 2019). The Eastern Cape province exhibits a high-class wind resource which can be exploited towards expediting such a transition to renewable energy.

Research into how South Africa's wind potential relates to the occurrence of specific synoptic types has been quantified by Landwehr et al., (2023) who identified three key synoptic states associated with high wind energy potential at WEFs in the Eastern Cape using SOMs. These synoptic states, occur predominantly during the (austral) winter and resemble the passage of a mid-latitude low pressure trough followed by a ridging anticyclone.

This paper takes the next steps towards quantifying the future variability and systematic changes in the wind resource as it relates to wind energy facilities in temporal and spatial dimensions, within the context of a changing climate. Using the synoptic typing approach, projected changes in the frequency of synoptic types associated with high and low energy production in a changing climate are presented.

GCM data from the Climate Model Diagnosis and Intercomparison Project (CMIP6) are used. Projection results show high wind energy producing synoptic systems frequencies decreasing from 2020 to 2090, and thus average P50 wind energy production shows consistent drop off which does not recover. Economic sensitivity analysis suggests that the overall impact of climate change could imply a decline in lifetime IRR.

This paper highlights the need to develop this long-term wind energy projection capability in South Africa to provide the data platform on which to base climate risk mitigation measures for WEFs.

Keywords:

Wind energy production projections, Changing climate, Global Climate Models

6.1 Introduction

As a percentage of the total global energy supply, wind energy facilities could provide 10% of the total global energy supply by 2050 (IEA, 2023). The South African Integrated Resource Plan (IRP) 2019, lays out the proposed generation new build fleet of power generation stations for South Africa for the period 2021 to 2030 giving wind priority (RSA Government, 2011).

The Eastern Cape Province of South Africa has a high potential for wind energy as can be seen by the conglomeration of planned and installed wind farms in this region. Recently, Landwehr et al. (2023) has explored the energy meteorology of the Eastern Cape Province in South Africa, using SOMs (Kohonen et al., 1996) to objectively identify 35 synoptic types for the Eastern Cape province from 6-hourly ERA5 geopotential reanalysis data (Hersbach et al., 2020b) for the period 2010 to 2019. The six-hourly accumulated wind energy production at several indicative facilities in the Eastern Cape were subsequently mapped onto the SOM, to obtain an estimate of the wind energy potential of each synoptic type.

The synoptic types most inductive to the wind potential over the Eastern Cape, produce strong southwesterly winds that result from the Atlantic Ocean High with its centre at about 30 °S ridging behind a cold front (Landwehr et al., 2023a). The synoptic type with the lowest energy potential is essentially the same pattern, but with the centre of the high displaced southwards to about 35 °S, ridging behind a mid-latitude cyclone that has followed a more southerly trajectory (Landwehr et al., 2023a).

The combined effects of global warming and Antarctic stratospheric ozone depletion has in recent decades resulted in a poleward displacement of the Southern Hemisphere westerlies, and associated storm tracks (Archer et al., 2018). Under low mitigation futures, despite the projected recovery of stratospheric ozone, the further poleward displacement of the westerlies is projected to continue (Archer et al., 2018). For the southern African region, such a change has been shown to co-occur, and to be partially forced by, the more frequent occurrence of southward displaced and blocking subtropical high-pressure systems, over and to

the south of South Africa (Archer et al., 2018). This change in the Hemispheric and regional circulation is the likely cause of a detectable decrease in rainfall in South Africa's winter rainfall region (Archer et al., 2018) with projected further decreases in a warmer world (Archer et al., 2018). Such changes may simultaneously result in a decrease in the wind potential of South Africa's southern provinces, particularly so in the Western and Eastern Cape, with their excellent wind-potential. However, climate change impacts on the renewable energy potential in South Africa has to date not been explored.

In this paper we consider the impact of climate change on energy production at four idealised WEFs in the Eastern Cape province of South Africa, making use of the methodology of Landwehr et al. (2023) and projected changes in the regional circulation as obtained from the GCMs of the Coupled Model Intercomparison Project Phase Six (CMIP6). This method and result provide the basis for comparing energy production of the base case decade 2010 – 2019 to the energy production of the future decades to show any decline or improvement in the spatial area of interest. The following sections outline how GCMs have been used to project the energy production of the Eastern Cape.

6.2 Geopotential

A standard output from climate models is the geopotential height at different pressure levels. Under geostrophic balance, the geopotential defines the wind-field at synoptic weather-system spatial scales. We have therefore developed a methodology that links six-hourly geopotential height at a given pressure level to wind energy generation over six-hourly periods. Over South Africa's Eastern Cape, the 1000 hPa geopotential height provides a reasonable approximation of the height at which the wind farms are located. Deeper into the interior, the 850 hPa geopotential height would be a better approximation to describe near-surface winds over the plateau. A practical disadvantage of our approach is that only a few CMIP6 modelling groups have made available six-hourly geopotential fields, so that the size of the multi-model ensemble we use in the paper to project changes

in future energy generation is relatively small. Larger available ensembles of mean sea-level pressure can be used to approximate in the same manner, near-surface wind fields for wind farms close to the coast. However, mean sea-level pressure patterns will be a less ideal for approximating wind patterns over the South African plateau. Our results are nevertheless limited by the relatively small size of the multi-model ensemble we use yet, they provide a clear demonstration of the methodology we propose to link projected future changes in circulation patterns to wind energy generation at much finer spatial scales.

6.3 Geography and energy meteorology of the Eastern Cape

The Eastern Cape, in the central southern part of South Africa, and with the Indian Ocean to its south, has high wind energy potential. The southern part of the province falls in South Africa's narrow all-year rainfall region, whilst the northern interior is a summer rainfall region (Engelbrecht, C. et al., 2013). Winter rainfall over the province originate from cold fronts that sweep over the area from west to east, followed by ridging high-pressure systems from the Atlantic Ocean, which function to strengthen the pressure gradient and contribute to the influx of cool and moist southerly air masses. During the transition seasons of spring and autumn, westerly cut-off low pressure systems from aloft, and ridging high-pressure systems at the surface, are the main rainfall producing systems (Engelbrecht, C. et al., 2013). Summer rain is largely convective and is partially the result of tropical troughs to the north of South Africa linking up with westerly waves passing over southern South Africa.

It is the proximity of the Eastern Cape to the westerly wind regime of the Southern Ocean that provides it with not only all-year rainfall, but also with an excellent wind potential. The South African Wind Atlas (WASA) wind speed map shows a significant part of the Eastern Cape Province having wind speeds higher than 8

m/s and this accompanied by the wind power densities¹¹ in the order of 800 – 1000 W/m² make the Eastern Cape viable for utility scale wind farm sites (CSIR, 2019). In comparison, all the other provinces other than the Western cape, which is more comparable to the Eastern Cape but with a more congested electricity grid, generally have lower wind speeds and wind power densities (Badger et al., 2022).

The energy meteorology of the Eastern Cape was objectively analysed by Landwehr et al. (2023), using a SOMs approach. The weather pattern most conducive of wind energy in the Eastern Cape consist of a mid-latitude cyclone passing to the south of the country, with the Atlantic Ocean High centred at about 30 °S ridging behind the cold front. For all three synoptic states, the net result is pronounced southwesterly flow over the Eastern Cape highlighting the importance of strong southwesterlies for wind energy generation in the Eastern Cape.

The circulation type and associated synoptic pattern that has the lowest energy generation potential for the Eastern Cape represents mid-latitude cyclones with a more poleward and eastward location and a ridging high pressure with centre at about 35°S. Pressure gradients are consequently weak over the Eastern Cape, and wind energy production is low (Landwehr et al., 2023a).

Most months exhibit the strongest winds around midday, especially in the interior this is mostly due to surface heating causing convection/ turbulence and subsequent mixing with the air aloft that blows in a certain direction. Generally average monthly wind speeds peak in winter and remain relatively high in summer. Closer to the coast however, wind speeds peak in spring and summer but remain relatively high in autumn and winter. Over the western interior, autumn and spring are seasons with high wind speeds at night, but with winter recording high values on the average right through the diurnal cycle (Landwehr et al., 2023a).

To explore in more detail the seasonality of energy production in the Eastern Cape, the monthly energy production per node was analysed. From this analysis the three nodes with the highest energy potential contribute most to annual production

¹¹ Power density is the mean annual power available per square meter of swept area of a suitable Wind Turbine Generator. Power densities more than 1000 W/m² which is exceptional.

during the winter months (June to August). This is not surprising, given that these nodes are associated with the passage of cold fronts over the Eastern Cape that occur in association with steep pressure gradients caused by the Atlantic Ocean High (Landwehr et al., 2023a).

6.4 Global climate models

The following sections provide a description of the global climate models and information used in this study and map out the methodology developed to project the 21st century wind energy production futures of the Eastern Cape.

Given that this is the first paper to objectively explore the projected wind energy futures of southern Africa, specifically for South Africa's Eastern Cape Province, it was decided to conservatively focus on low mitigation greenhouse gas emission futures, under which the climate change signal is the strongest. Thus, projections from the Coupled Model Intercomparison Project Phase Six (CMIP6) under SSP 3-7.0 (high aerosol emissions and roughly double CO₂ emissions from current to 2100) and 5-8.5 (roughly double CO₂ emissions from current to 2050) (Chen et al., 2021) have been utilised.

The name of individual SSP is made up of the name of the basic pathway and then two numerals indicating the additional radiative forcing achieved by 2100 in units of tenths of watts (Government of Canada, 2022, German Climate Centre, 2022).

For the purposes of this study, SSP370 and SSP585 have been selected to provide strong climate change signal and thus a potentially cause the largest change in outlook for wind energy production in a changing climate. SSP370 is a conservative scenario in which local issues are in focus with high consumption, and with low importance placed on environmental issues (Government of Canada, 2022, German Climate Centre, 2022). SSP585 is a progressive scenario with focus on investments in wellbeing and intensive fossil fuel usage to sustain this focus (Government of Canada, 2022, German Climate Centre, 2022). The CMIP6 simulations are available for the historical period 1850-2014, during which

observed or reconstructed radiative forcing was applied to the models. For the period from 2015 onwards, the radiative forcing is as per the SSP used in the simulation.

For some of the CMIP6 GCMs, initial condition ensemble simulations have been produced per SSP. In this research, following Lee et al. (2021), we select only the control simulation generated for each ensemble. This avoids issues of model weighting that need consideration when ensembles of various sizes per GCM need are used. Some of our results are presented as a function of the level of global warming. Warming levels are defined as the 20-year period centred around the year for which the 20-year running mean first exceeds a certain level of warming relative to the average global surface temperature of the pre-industrial era of 1850 to 1900, following the methodology of Lee et al. (2014). Note that the period 1850-1900 has been used in the IPCC AR6 to approximate the pre-industrial period, although some anthropogenic warming was already present during this period (Gutiérrez et al., 2021). The approximation is made given the relative abundance of meteorological data from 1850 onwards (WCRP, 2023).

The following global warming levels have been used as markers at which to compare the change in energy production to a present-day baseline: 1.0 °C, 1.5 °C, 2.0 °C, 3.0 °C (Hauser et al., 2022).

6.4.1 Available GCMs

The methodology of Landwehr et al. (2023), which mapped wind energy production in the Eastern Cape onto objectively identified synoptic types using a SOM, made use of 6-hourly 1000 hPa geopotential heights, obtained from ERA5 reanalysis data (Hersbach et al., 2020b). We consequently selected from the CMIP6 archive available via the Earth System Grid (WCRP, 2023) the GCMs that have 1000 hPa geopotential heights at six hourly intervals, for one or both low mitigation scenarios SSP370 and SSP585. Only five of the CMIP6 GCMs had available 1000 hPa geopotential heights at 6-hourly intervals, with four others being at daily intervals converted to 6-hourly by applying a method of interpolation using the trained SOM

results and the patterns binding any particular day. The GCM fields were all interpolated to a common 1° resolution latitude-longitude grid.

6.4.1.1 NORESM2

The Norwegian Earth System Model version 2 (NorESM2) has versions NorESM2-MM (1° resolution for all model components) and NorESM2-LM (2° resolution for the atmosphere and land components; 1° resolution for the ocean and sea-ice components). Both models had 6-hourly geopotential data available for both SSP370 and SSP 585 (NCC, 2022).

6.4.1.2 MPI-ESM1-2

The MPI-ESM1-2-LR is a low-resolution version of the Max Planck Institute Earth System Model (MPI-ESM). It has a horizontal resolution of roughly 2° for the atmosphere ocean. The model has 6-hourly 1000 hPa height projections available for both SSP370 and SSP585 (Gutjahr et al., 2018).

6.4.1.3 CANESM5

The Earth System Model from Canada, version 5 (CanESM5) is a GCM comprised of three-dimensional atmosphere (roughly to 2.8°) and ocean (nominally 1°) general circulation models This model is available in SSP370 and SSP585 (Swart et al., 2019).

6.4.1.4 EC-Earth3-AerChem

EC-Earth3 is developed by the EC-Earth European research consortium. There are eight different (tuned) EC-Earth3 configurations, with one of them being AerChem, used for climate change projections. It features an atmospheric resolution of 0.7°. This model is only available in SSP370 (Döscher et al., 2021).

6.4.2 Warming levels

The following table provides the 20-year period for the chosen warming level thresholds for the relevant models in question (Hauser et al., 2022).

Table 6-1: GCM Warming levels (Hauser et al., 2022)

No.	Model	Experiment	Warming Level	Start Year	End Year	Median Year
1	NorESM2-LM	ssp370	1	2023	2042	2032
	NorESM2-LM	ssp370	1.5	2042	2061	2051
	NorESM2-LM	ssp370	2	2060	2079	2069
2	NorESM2-MM	ssp370	1	2022	2041	2031
	NorESM2-MM	ssp370	1.5	2037	2056	2046
	NorESM2-MM	ssp370	2	2053	2072	2062
	NorESM2-MM	ssp370	3	2081	2100	2090
3	NorESM2-LM	ssp585	1	2014	2033	2023
	NorESM2-LM	ssp585	1.5	2033	2052	2042
	NorESM2-LM	ssp585	2	2047	2066	2056
	NorESM2-LM	ssp585	3	2068	2087	2076
4	NorESM2-MM	ssp585	1	2016	2035	2025
	NorESM2-MM	ssp585	1.5	2030	2049	2039
	NorESM2-MM	ssp585	2	2045	2064	2055
	NorESM2-MM	ssp585	3	2067	2086	2077
5	MPI-ESM1-2-LR	ssp370	1.5	2026	2045	2035
	MPI-ESM1-2-LR	ssp370	2	2043	2062	2052
	MPI-ESM1-2-LR	ssp370	3	2069	2088	2078
6	MPI-ESM1-2-LR	ssp585	1.5	2025	2044	2034
	MPI-ESM1-2-LR	ssp585	2	2039	2058	2048
	MPI-ESM1-2-LR	ssp585	3	2062	2081	2071
7	CanESM5	ssp370	2	2014	2033	2023
	CanESM5	ssp370	3	2034	2053	2043
8	CanESM5	ssp585	2	2013	2032	2022
	CanESM5	ssp585	3	2031	2050	2040
9	EC-Earth3-AerChem	ssp370	1	2009	2028	2018
	EC-Earth3-AerChem	ssp370	1.5	2023	2042	2032
	EC-Earth3-AerChem	ssp370	2	2038	2057	2047
	EC-Earth3-AerChem	ssp370	3	2057	2076	2066

6.5 Methodology

6.5.1 *ERA5 Long term variability*

To rule out any possible long-term variability in the observed ERA5 dataset with respect to node frequency, the frequency distribution of the BMUs of the 2000 – 2009 data was compared to that of 2010 – 2019. This was completed by obtaining the ERA5 geopotential dataset for 2000 to 2009 and regridding it to 1°. All the timestamps were then individually extracted and the average for the spatial focus area was subtracted. This dataset was then run through a Pearson correlation to determine the frequency of synoptic types when compared to the original trained SOM in the concurrent period.

6.5.1.1 GCM evaluation

To determine how well the global climate models predict the occurrence of the SOM patterns extracted from the ERA5 datasets, a similar process was completed to the ERA5 long term variability process above. Initially, the GCM 2010 to 2100 data was obtained and regridded to 1°. All the timestamps were then individually extracted and the average for the spatial focus area was subtracted. This dataset was then run through a Pearson correlation to determine the frequency of synoptic types when compared to the original trained SOM¹² in the concurrent period. This result allowed for the calculation of the correction factors required to return the GCM pattern frequencies to the observed frequency of the trained SOM (Teutschbein et al., 2012). The projected GCM timeseries frequency can then be corrected.

¹² Note that for GCM's with daily frequency, the same Pearson correlation approach has been applied however to align the sample size with the 6 hourly GCM's, an interpolation is performed to synthesize timesteps to convert daily mean to 6 hourly. This is done by multiplying the daily frequency by four. This result is very similar to that of taking the CDO ENSMEAN three times and performing the correlation. The advantage of this method is that the results are bound by the daily correlation result of the daily resolution GCM to the trained SOM.

6.5.1.2 Wind energy projections

Once the frequency for the concurrent period for the GCM has been corrected, it can then be projected to determine the frequency of the synoptic types and in turn the energy production for future decades. This is accomplished by running the Pearson correlation to determine the frequency of synoptic types in the projected timeseries and applying the frequency correction factors for each SOM node. Finally, the energy production per MW installed can be applied per node to the calculated frequency to determine the energy production per MW installed for every year until 2100.

6.5.1.3 Wind energy economic impacts

These changes in very long-term wind energy production have implications on revenues produced at each WEF. A sensitivity analysis of this cost impact is thus carried out for a medium size WEF aligned with what is common in the South African Renewable Energy Independent Power Producers Procurement Programme (REIPPPP) latest bidding rounds (IPPO, 2021). This analysis is also carried out in three relevant PPA periods namely 2021-2040, 2041-2060, 2061-2080 and for an ensemble of GCMs and the GCMs separately.

The approach taken to derive such revenue insights is based on an estimation of the internal rate of return (IRR) for an ideal base case WEF versus the IRR from the same WEF but with projected energy production impacted by climate change. To be able to provide such estimates, several reasonable assumptions need to be made as follows (summarised in Table 6-2):

6.5.1.3.1 Tariffs

The most recent publicly bid WEF tariffs are from the REIPPPP Round 5 public auction (IPPO, 2021). These tariffs can be used as proxy for projects starting in 2021 and then assuming that the same tariff will be valid for subsequent PPA periods.

6.5.1.3.2 Capital Expenditure (CAPEX)

The lifetime CAPEX investment for a WEF is made up of three major key components namely the procuring the WTGs, construction of the electrical balance of plant (EBOP) and construction of the civil balance of plant (CBOP). To arrive at a reasonable assumption for CAPEX, the REIPPPPP Bidding round 5 average tariff was used in conjunction with the average AEP per MW installed provided in Paper 1 (Landwehr et al., 2023a).

6.5.1.3.3 Long term loss assumptions

For the comparison of the same WEFs energy production without and with climate change impacts, no degradation and availability has been considered since these would be common to both scenarios.

Furthermore, no PPA Period Energy Escalation has been considered due to improved technology as this would be common to both scenarios as well.

6.5.1.3.4 Energy production

To calculate this energy on an annual basis for this analysis, the availability loss included in the original AEP calculations is removed and an annually varying degradation and availability can then be applied. This CAPEX is then adjusted upwards in reasonable increments for later PPA periods. This is used to calculate the revenue generated from the WEFs.

The energy production including climate change impacts is calculated using the projected energy production at an ensemble GCM level and an individual GCM level.

Once again, it is critical to remove the availability loss included in the original AEP calculations and then apply an annually varying degradation and availability for the lifetime of the plant.

Table 6-2: General assumptions used in the economic analysis (IPPO, 2021)

Lifetime	20	Years
Base Tariff	0.7	ZAR/kwh
Base Tariff	0.035	\$ / kWh
CAPEX	1 750 000	\$ / MW installed
Exchange rate	20	\$ / ZAR
Discount rate	10	%
PPA Period 1	2021-2040	
PPA Period 2	2041-2060	
PPA Period 3	2061-2080	

6.6 Results and Discussion

6.6.1 ERA5 Long term variability

Figure 6-1 is the result of the comparison between the two decades 2000-2009 and 2010-2020 of the ERA5 observed frequency for each of the SOM Nodes. From visual inspection, there is minimal difference between the two and thus no obvious need for any long-term adjustment.

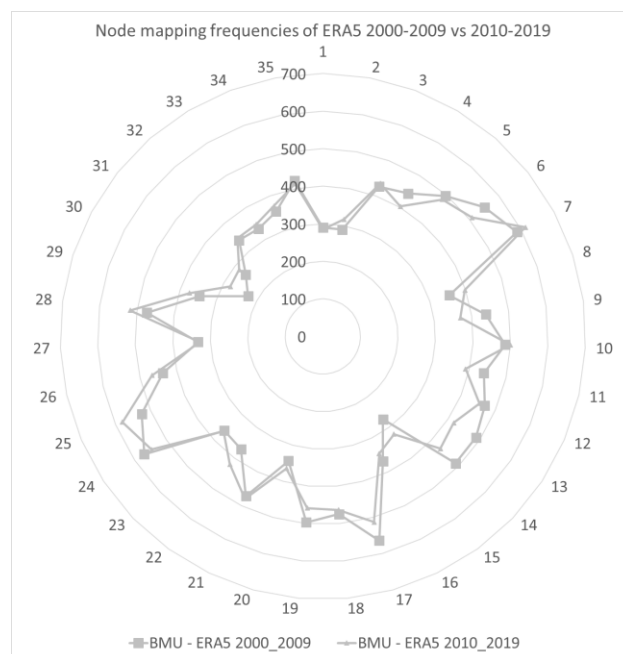


Figure 6-1 Node mapping frequencies of ERA5 2000 – 2009 vs 2010 – 2019

Taking the above result from the 2000-2019 ERA5 data and overlaying the trained SOM synoptic type frequency per trained SOM node (red), Figure 6-2 demonstrates some slight differences between the two. This is due to the way the SOMPAK © software reduces dimensionality in simplifying large amounts of data into a selection of representative datapoints (Kohonen et al., 1996), whereas the mapping result from the ERA5 dataset is purely based on the Pearson pattern correlation to the trained SOM node patterns.

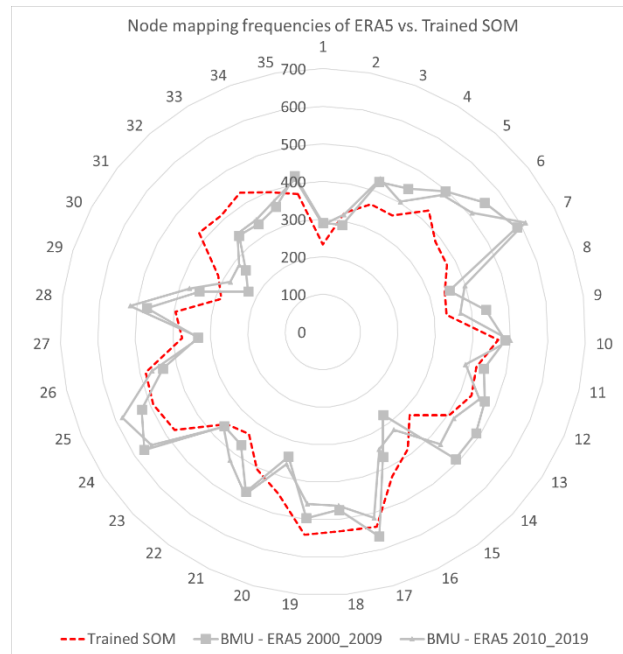


Figure 6-2 Trained SOM frequency versus ERA5 Pearson Correlation frequency

6.6.2 GCM evaluation

The average of the frequency correction factors per GCM is provided below alongside the Standard Deviation as a % of the overall mean.

Table 6-3: Average Node frequency correction factors used for each model

No.	Model	Average Correction Factors	Standard Deviation as % of Mean
1	NorESM2-LM-370	1.10	32.4%
2	NorESM2-MM-370	0.98	18.8%
3	NorESM2-LM-585	1.11	33.6%
4	NorESM2-LM-585	0.98	19.5%
5	MPI-ESM1-2-LR-370	1.33	54.0%
6	MPI-ESM1-2-LR-585	1.35	57.7%
7	CanESM5-370	3.15	81.1%
8	CanESM5-585	3.04	84.8%
9	EC-Earth3-AerChem-370	1.26	43.4%

6.6.3 Wind energy projections

After performing the Frequency correction for each of the GCMs and aggregating the results into an ensemble of nine GCMs, the top four wind energy producing synoptic type frequencies can be compared at the threshold temperatures of 1.0 °C, 1.5 °C, 2.0 °C and 3.0 °C (Figure 6-3). It can be observed that there is a general decrease in their frequency however this is not consistent for each temperature threshold. For example, for the nodes 8 and 15, the frequency change for 1.0 °C, 1.5 °C and 3.0 °C is downwards however at 2.0 °C, there is a clear upward spike. This upward spike doesn't however make much difference and the overall ensemble energy production still declines over the 2020 to 2090 period.

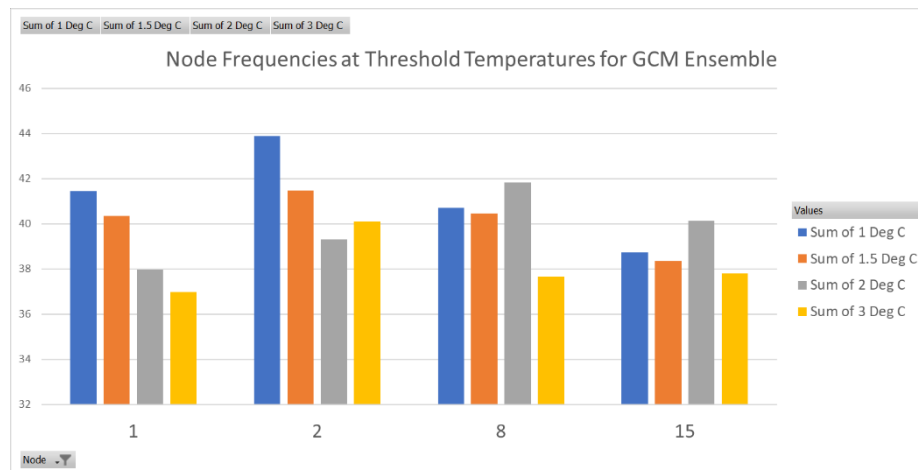


Figure 6-3 Node frequency change – Top four wind energy producing nodes

The opposite is true for the bottom four wind energy producing synoptic systems in that there is generally an increase in their frequency of occurrence (Figure 6-4). However once again, this is not always the case and for 2.0 °C and 3.0 °C in the below figure there is some decline noticeable. Due to the lower energy producing strength of these systems, the overall ensemble trend ends up being downwards as per Figure 6-6 and Figure 6-7.

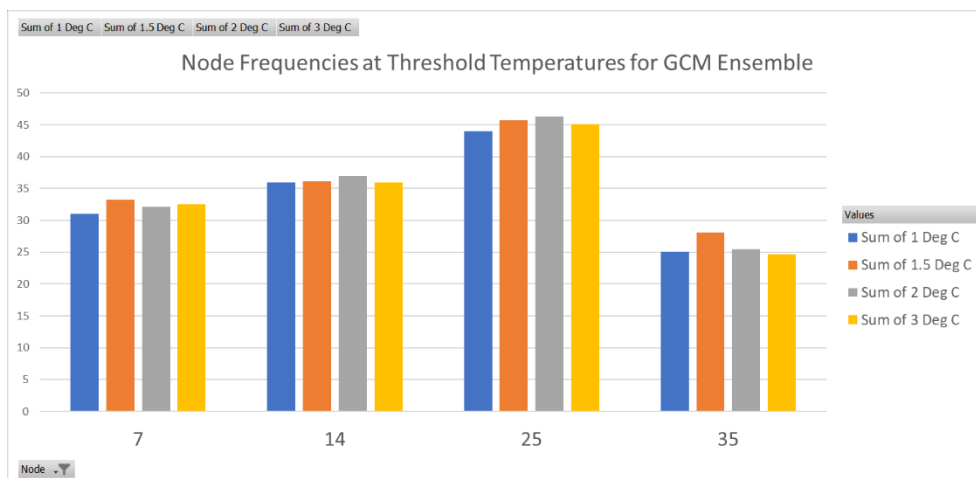


Figure 6-4:Node Frequency Change – Bottom four wind energy producing nodes

The result is an overall reduction in P50 energy production per MW installed as can be seen from the ensemble average energy production for all nodes at the threshold temperatures at each increment of warming (Figure 6-5).

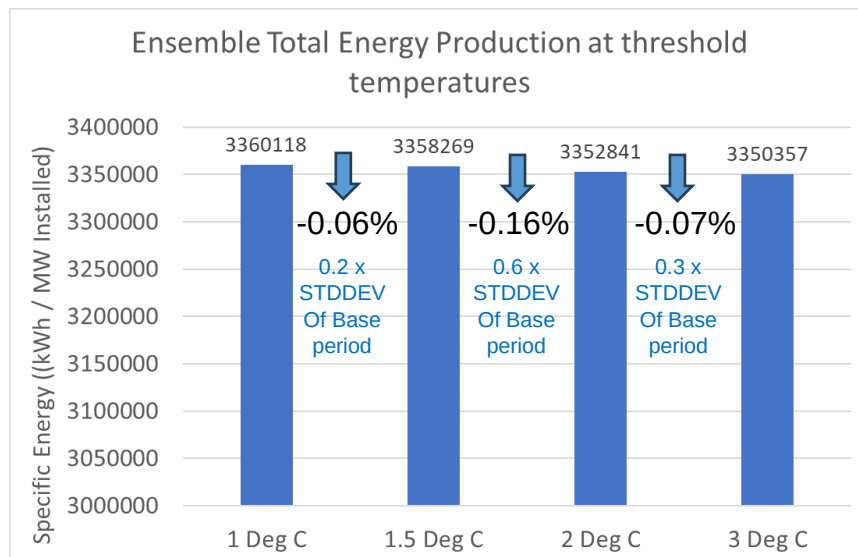


Figure 6-5 Average P50 energy production change at threshold temperatures

Qualitatively, these projected decreases in high-energy nodes, and increases in low energy nodes, are consistent with the poleward shift of the Southern Hemisphere Westerlies, a change that can already be detected and is projected to intensify under low mitigation futures (Lee et al., 2021). Such a change is projected to co-occur with the strengthening of the descending branch of the Hadley Cell over southern Africa and the more frequent formation of subtropical highs over and blocking highs to the south of South Africa (Engelbrecht, F. et al., 2009, Engelbrecht, C. et al., 2013).

Extending the above to all years from 2020 to 2090, the 20-year average, ensemble averages show consistent drop off in P50 energy production per MW installed. This drop off does not recover in any of the GCMs and is an indication that there will be a general reduction in wind energy production from 2020 to the end of the century (Figure 6-6).

When applying the Sen slope and M-K test (Sen, 1968, Kendall, 1948, Mann, 1945) to determine the statistical significance of the energy production timeseries, the following results were found:

- S-Statistic: -2411
- Variance of S: 38908
- Z-Statistic: -12.22
- Sens slope: -1328.6

These results show a statistically significant negative trend in the energy data which decreases by approximately 1328.6 kWh / MW Installed per year.

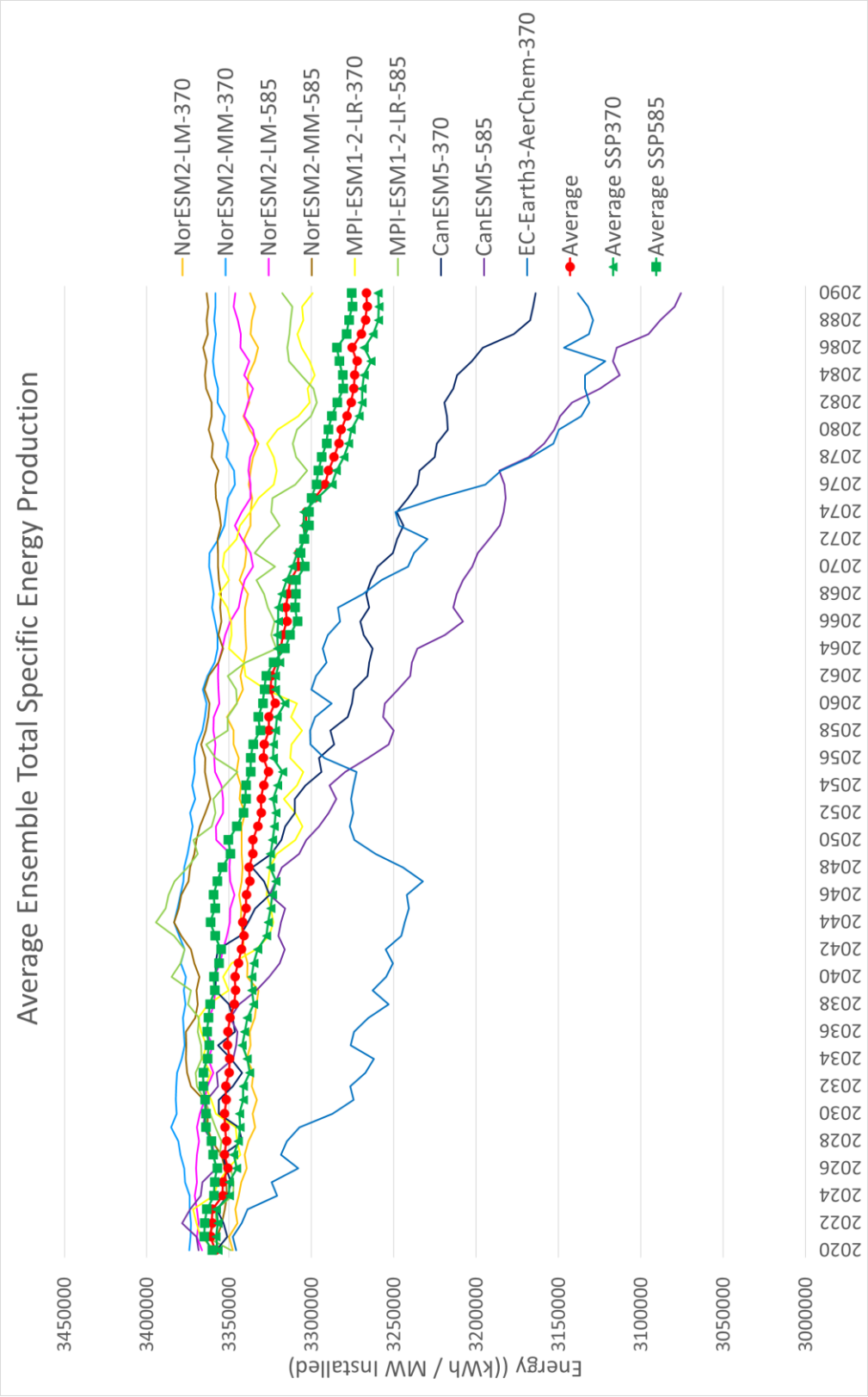


Figure 6-6 Time series of projected P50 energy production change for each GCM and each scenario

Selecting specific nodes to illustrate the difference in how the P50 energy production changes at higher granularity clearly shows that some nodes increase, and others decrease in energy production. In general, however the higher wind energy producing nodes show a decline and thus have a higher impact on the overall energy production. Nodes 8 and 1 show this decline whereas lower energy producing nodes such as 7 show an increase.

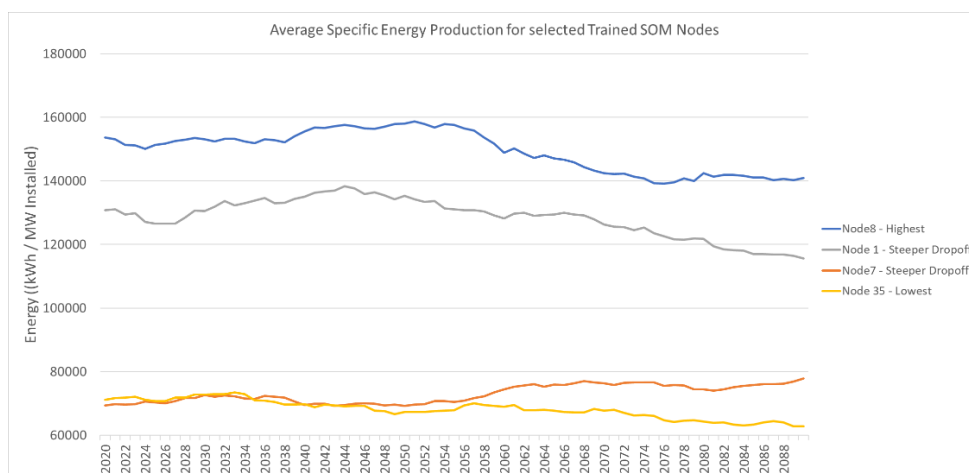


Figure 6-7 Projected P50 energy production change for selected SOM nodes

6.6.4 Wind energy economic impacts

Initially, the overall difference between a 140 MW WEF IRR excluding and including climate change impacts for the CMIP6 GCM ensemble P50 energy production is investigated but further granularity is achieved by looking at how each of the GCMs performs alone in Figure 6-8.

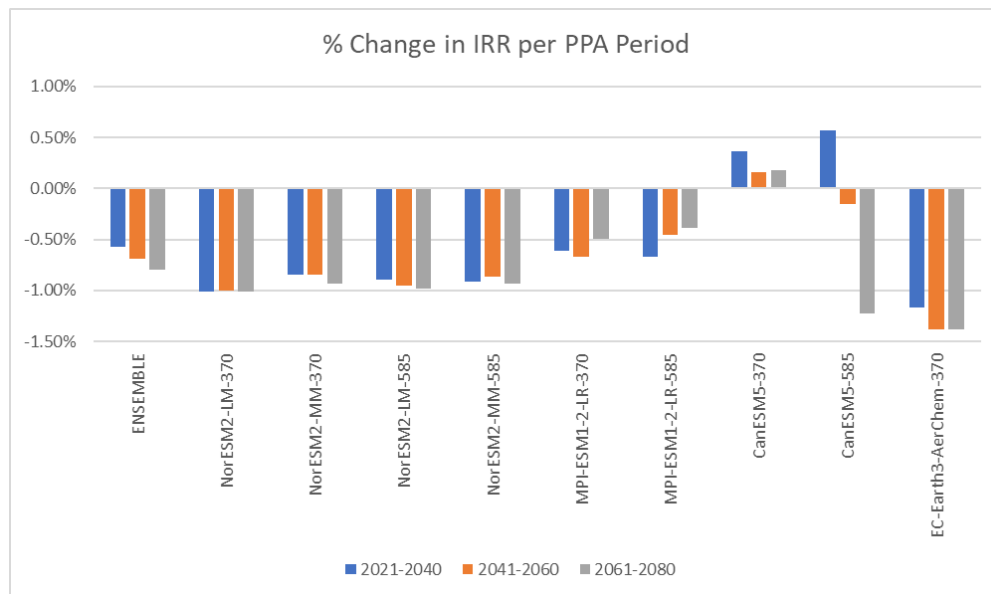


Figure 6-8: Comparison of % Decrease in IRR per PPA Period for each GCM (IPPO, 2021)

Considering the complete ensemble results, the IRR declines in all three PPA periods and gets worse from PPA period one to three from -0.6%, -0.7% and -0.8% respectively over the lifetime of the WEF. These GCM specific results are aligned with a similar study carried out in 2023 where three sites using three socioeconomic pathways also for an ensemble of CMIP6 GCMs were considered showing a maximum decline in the IRR over the lifetime of the WEF from between 0.1 to 0.6% (Gebraad, et al., 2023). The sites considered were closer to the Equator in Brazil and Europe and thus slightly higher IRR impacts are projected due to the lower latitudes of this study.

If we consider the GCMs individually it can be observed that the NorESM2 GCMs show a decrease in lifetime IRR of between -0.8% and -1% for all PPA periods which contrasts with those displayed by the CanESM5 GCMs which show even an increase of 0.6% to a decrease of -1.2%. These figures are slightly lower for MPI-ESM2 with decreases ranging between -0.4% and -0.7%. This is even more pronounced for EC-Earth3 with decreases ranging between -1.2% and -1.4%.

This spread of results highlights the importance of using a suitably sized ensemble of GCMs to arrive at a more robust outcome catering for any anomalous outliers.

6.7 Conclusion

At present, there exists a prevailing positive outlook for renewable energy, in particular wind energy, globally and in South Africa. For this reason, it is important to quantify the future wind energy production from WEFs in a changing climate. In this study, we apply a novel approach of identifying projected changes in the frequency of synoptic circulation states associated with high and low energy production in the South Africa's Eastern Cape region using trained SOM results from (Landwehr, et al., 2023a) and developing projection data from nine GCMs under two emissions scenarios. These changes in frequency are applied to specific wind energy production in the Eastern Cape Province and the economic impact is investigated based on a plausible WEF size aligned with what is common in the REIPPPP latest bidding rounds. Of course, only nine GCMs poses limitations in this study since this is a small ensemble. It does however allow for a clear depiction of the methodology proposed.

The patterns displayed for the high energy producing synoptic systems point to the tropical and temperate disturbances across South Africa and show patterns resembling an anticyclone off the west coast of South Africa and low-pressure troughs to the north and southeast of the country. The pressure gradient between the high and low-pressure trough is at a maximum in nodes 8 and 15, resulting in strong wind energy potential.

Projections of the frequency of these high energy synoptic states show a decrease at all global warming temperature thresholds. Thus, a decrease in P50 wind energy production is projected as a result of a declining number of high energy producing synoptic systems over the region.

Low energy producing patterns are characteristic of the high-pressure cells moving southwards producing fine weather and mildly disturbed conditions. This is characteristic of node 7 (Landwehr, et al., 2023a), whose frequency is projected to increase. This, however, does not offset the decreased frequency of the high energy producing nodes and a net decline in energy production in the focus area is projected across all warming temperature thresholds.

The likely cause of this circulation change is the poleward expansion of the descending limb of the Hadley circulation. This (1) displaces frontal system southward together with the high-pressure systems off the southwest coast associated with high energy production and (2) the centre of the Kalahari High over the interior shifts southward towards the study region, recognising that winds associated with high pressures are weakest at the centre of the system and strongest at the edges.

Further extending this result to understand the economic impact of this P50 energy production change, a 140 MW WEF IRR excluding and including climate change impacts for the CMIP6 GCM ensemble energy production is investigated. Results show that the IRR for the ensemble in PPA period one to three at -0.6%, -0.7% and -0.8% respectively over the lifetime of the WEF. This is even more pronounced for EC-Earth3 extending in the third PPA period to as high as -1.4%. This could negate a project from being pursued if the IRR drops below the acceptable limits.

This study demonstrates that WEF developers, in this spatial area but also more generally, need to be cognizant of the impact climate change will have on the wind energy climate affecting the region and the concurrent implications for energy and revenue production. Further research could be conducted to analyse projected wind energy production changes in different parts of South Africa as well as globally where the wind energy potential is currently high.

6.8 Author contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Greg Landwehr, and supported by Francois Engelbrecht and Chris Lennard. The first draft of the manuscript was written by Greg Landwehr and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

6.9 Declarations

6.9.1 *Funding*

Funding: This work was supported by the National Research Foundation of South Africa through its Earth System Science Research Programme, Grant 118598.

6.9.2 *Conflict of Interest Statement*

All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

6.9.3 *Data Availability Statement*

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

We acknowledge the World Climate Research Programme, which, through its Working Group on Coupled Modelling, coordinated and promoted CMIP6. We thank the climate modelling groups for producing and making available their model output, the Earth System Grid Federation (ESGF) for archiving the data and providing access, and the multiple funding agencies who support CMIP6 and ESGF.

CHAPTER 7: PAPER 3 – Securing the wind energy future of South Africa’s Eastern Cape Province by assessing and mitigating climate change Risk

Submitted and under peer review with Theoretical and Applied Climatology

Impact Factor 3.41

Date Submitted: 28 February 2024

Submission ID: 48b2a461-84c0-4ce9-8511-36b359316660

Contributions:

Gregory Landwehr (80%)	Francois Engelbrecht (12%)	Chris Lennard (8%)
• Conceptualization • Data curation • Formal analysis • Investigation • Methodology • Project administration • Writing - original draft • Writing - review & editing	• Conceptualization • Funding acquisition • Methodology • Project administration • Supervision • Writing - review & editing	• Conceptualization • Methodology • Supervision • Writing - review & editing

7. Paper 3 (Chapter 7) in the context of Paper 1 (Chapter 5) and Paper 2 (Chapter 6)

The progress made and challenges faced in South Africa towards transition away from coal towards renewable energy, are assessed in this chapter, within the context the current state of the energy sector and the increasing impacts of climate change.

After examining the case for a rapid transition to renewable energy in South Africa, Paper 3 (Chapter 7) then proceeds to demonstrate the importance of long-term wind energy projections to understand how wind energy production and WEFs may be impacted by a changing climate. Such capability can be developed using the methodologies presented in Paper 1 (Chapter 5) and Paper 2 (Chapter 6), which effectively translates the ability to predict change in frequency of high wind energy producing weather systems. Given that the derived projections show a likely decrease in the country's wind energy production potential in the Eastern Cape Province, being able to predict wind potential nationally will also become more important.

Paper 3 (Chapter 7) identifies possible climate change impact areas for WEFs and presents ways to mitigate these impacts. It also reiterates the need for building this capacity and concludes by presenting a practical way of implementing this.

Abstract

The share of the total installed power capacity held by wind energy facilities in South Africa will increase substantially by the late 2020s. This is according to the current South African Integrated Resource Plan, which aims to procure 1.6 GW of Wind power per year to 2030. Furthermore, with the looming decommissioning of Eskom (the national electricity provider) coal fire power plants and the aging nature of its only nuclear power plant, the knock-on effects of extended high impact load shedding implies that the need for renewable energy facilities has never been more important.

However, South Africa, through Eskom, has experienced challenges to meet the energy demand of its citizens and industries, let alone achieve or develop a transparent plan for a transition to renewable energy. This is due to grid capacity issues, and the associated slow rollout of new generation capacity. These are not unsolvable stumbling blocks and with better queuing rules for grid space, efforts to expedite grid and generation capacity expansion and an ongoing transparent renewable energy procurement programme, confidence can be restored amongst the public and investors. The latest Eskom transmission development plan heavily emphasizes building out the grid over the next 10 years, to facilitate the projected renewable energy production growth.

Although the number of WEFs are currently growing in South Africa, in a changing climate where temperatures in South Africa are projected to increase drastically under low mitigation futures, understanding the performance and impact of climate change on these facilities, is important for the sustainability of the South African energy system as it transitions to renewables.

In this paper the imperative for the identifying climate change risk and mitigation measures impacting WEFs in South Africa is outlined. Such a system will allow for strategic planning and the optimal management of South Africa's growing renewable energy network. Moreover, such capacity will also enable planning for the growing impacts of climate change on South Africa's renewable energy potential.

Keywords: Onshore WEFs, South African Energy System, Climate change risk assessment and mitigation

7.1 Introduction

A transition to renewable and sustainable energy in South Africa is a possibility in the 2020s and 2030s, if steps are taken to achieve this (RSA Government, 2019). Global trends show that renewable energy will achieve an annually installed capacity higher than fossil fuel based non-renewables from around 2030 onwards with onshore wind making up 25% of the total share by 2050 (IEA, 202). The South African Renewable Energy white paper published in 2003 highlighted the renewable energy potential in South Africa (RSA DoME, 2003b). This is bolstered by the latest South African Integrated Resource Plan (IRP) of 2019, which lays out the proposed new build fleet of power generation stations until 2030. Wind energy has been given priority (RSA Government, 2019).

However, South Africa has experienced some significant headwinds in its attempt to provide enough energy to its citizens through the state-owned power utility, Eskom. The stunting of the public renewable energy procurement process in 2022 where no wind energy facilities (out of twenty-three bids) were awarded preferred bidder status, due to a lack of grid capacity, has pushed the market more towards private offtakers who have effectively locked up the grid capacity and thus halted progress on many well-developed wind and solar renewable energy generation projects (SAWEA, 2023b).

The likely, although delayed, growth in South Africa's renewable energy sector creates an imperative to understand how wind energy facilities will perform in terms of generation in the context of climate change which, in turn, impacts weather patterns and consequently wind energy production potential. In particular, temperatures in South Africa are projected to increase at a drastic rate under low mitigation futures (CSIR, 2022a, Engelbrecht, F. et al., 2018), with associated increases in heat-wave frequencies and intensity. This implies a great demand for energy to achieve human comfort in houses and in buildings and to supply water.

To understand the long-term performance of wind energy facilities in a changing climate, a modelling methodology was developed in Chapters 5 and 6 of this thesis for the Eastern Cape province of South Africa (Landwehr et al., 2023a, Landwehr

et al., 2023b). Synoptic patterns associated with high wind energy production in the region have been identified using climate reanalysis data (ECMWF, 2021) and a synoptic typing methodology (Kohonen et al., 1996). The patterns are representative of various stages of a deep mid-latitude cyclone passing to the south of the Eastern Cape, with the Atlantic Ocean High ridging behind the cold front over the Eastern Cape of South Africa (Landwehr et al., 2023a). Thereafter, long term projected wind energy production was assessed using a newly proposed methodology and data from nine GCM simulations (Landwehr et al., 2023b).

The methodologies and information provided in (Landwehr et al., 2023a, Landwehr et al., 2023b) are the basis for this paper in which the global and local energy landscape is presented from a climate change perspective to show that a climate change risk assessment and mitigation capability for WEFs in South Africa is important and achievable.

7.2 Background

The world is entering a sustained period where energy systems will become more efficient and affordable, implying a lesser spend on energy as a proportion of Gross Domestic Product (GDP), and in turn providing Governments with confidence to accelerate the transition (DNV, 2022). This is happening in parallel with the need for bold policy choices in the context of climate change, towards the development of pathways to net zero greenhouse gas emissions. Regional cooperation across country boundaries and cross-industry cooperation will be critical, with 'power to X'¹³ and green hydrogen technologies, and shipping corridors becoming more and more prominent (DNV, 2022). An improved understanding on the efficiency of WEFs as a function of weather patterns, seasonality, inter-annual variability and a changing climate will be critical to manage a future energy system

¹³ Power to X: is a general term used to describe the use of renewable energy to power any kind of industry i.e. the 'X' in the term.

7.2.1 Global Energy System

The Global Energy Transition outlook and regional forecast to 2050, published by Det Norske Veritas (DNV) (DNV, 2022), states that in the short-term, high-energy prices and a greater focus on immediate energy security in the aftermath of Covid-19 and due to the war in Ukraine will not slow the long-term transition to renewable energy.

The Intergovernmental Panel on Climate Change (IPCC)¹⁴ assessment reports point out the increasing harmful impacts of climate change should global warming exceed the 1.5 °C and then 2 °C level of global warming (Hoegh-Guldberg et al., 2019), and as a result it is projected that the critical mass achieved to date in the drive to net zero emissions will eventually shift momentum back from the current focus on immediate energy security to a green energy future and climate change mitigation. This trend will result in fossil fuels having below 50% of the global energy share by 2050 (DNV, 2022). However, it is important to note that in order to keep global warming safely below 2 °C, net-zero emissions, and a complete phase-out of coal and oil, is required by 2050 (Rogelj et al., 2018).

A pathway to net zero requires global scale early action to reduce emissions and the window of opportunity to avoid dangerous and irreversible climate change is rapidly closing (Hoegh-Guldberg et al., 2018). To avoid catastrophic warming, policies must change to secure net zero emissions by 2050 (DNV, 2022).

Currently, the overall global grid-connected electricity generation is 27.5 Petawatt hours (PWh) per year (2022 estimate), which is expected to more than double to 61.5 PWh per year by 2050 (DNV, 2022). South Africa currently produces about 0.245 PWh, which is 0.9 % of the global production and the largest in Africa (22nd in the world) (BP Energy, 2021). Renewable energy is projected to take a large share of the overall energy mix by 2050, providing ~50 PWh/yr (DNV, 2022).

¹⁴ Intergovernmental Panel on Climate Change: a body within the United nations with the aim of advancing scientific understanding about climate change

7.2.2 South African energy system

South Africa is a relatively small greenhouse gas emitter when compared to the larger economies of China, the U.S.A., India, the EU and the Russian Federation, who are jointly responsible for about 60% of global emissions. However, on the African continent South Africa's emissions are the highest and its reliance on fossil fuels is also considered high relative to global norms. South Africa also remains the largest coal producer in Africa having a workforce of approximately 100 000 employees directly attached to this industry (Statistics South Africa, 2019).

As a signatory to the Paris Agreement on Climate Change, South Africa's greenhouse gas emissions are anticipated to reach their highest levels in 2025 before starting to decline. Total greenhouse gas emissions from the energy sector amount to close to 80% of South Africa's total greenhouse gas emissions (RSA Government, 2019). This commitment, as well as the aging fleet of coal-fired generation plants, means the transition to renewable energy sources is vital.

South Africa possesses a large wind energy reserve (CSIR, 2022a, RSA DoME, 2023b). However, the impact of the Covid-19 pandemic and low grid connection capacity has stemmed the influx of foreign investment in renewables in South Africa and Sub-Saharan Africa, stunting progress in this sector. Despite these setbacks, it has remained a high priority.

7.2.2.1 Key Policies, Plans, Programmes

This section reviews the key policies and programmes developed over the last 25 years to ensure South Africa's energy security and transition from an energy system based on fossil fuels to one based on renewables.

7.2.2.1.1 White Paper on energy policy in South Africa

The Department of Minerals and Energy (DME) produced a white paper in 1998 to clarify government policy regarding the supply and consumption of energy until 2008. The policy shows a willingness to bring about extensive change in several areas, including a renewables rollout (RSA DoME, 2023b).

7.2.2.1.2 White paper on renewable energy in South Africa 2003

This White Paper on Renewable Energy (RSA DoME, 2003b) supplements the White Paper on Energy Policy (DME, 1998) and further reiterates the potential of renewable energy in South Africa was significant. This Paper set out the South African Government's vision, policy principles, strategic goals, and objectives for promoting and implementing renewable energy in South Africa. It also informed the public and the international community of how the South African Government intends to achieve these objectives (RSA DoME, 2023b).

7.2.2.1.3 Integrated Energy Plan for South Africa 2003

The purpose of the integrated energy plan was to balance energy demand with supply resources in conjunction with safety, health, and environmental considerations. It was not meant as a precise blueprint for the energy sector but is a framework within which specific energy development decisions could be made with a particular focus on rolling out renewables (RSA DoME, 2003a).

7.2.2.1.4 Integrated Resource Plan for electricity in South Africa 2011

This document outlined the proposed new build fleet of power generation stations for South Africa between 2010 and 2030. The plan was based on a solution for new build options that was optimal in terms of least cost of energy resources at that time, weighed against key factors such as job creation (RSA Government, 2011).

7.2.2.1.5 Integrated Resource Plan 2019

The IRP 2019 is the successor to the IRP 2011 (RSA Government, 2011) and provides an infrastructure development plan for the electricity sector based on least-cost electricity supply and demand balance, considering security of supply and the environment to ultimately minimize emissions and water usage (RSA Government, 2019).

The IRP 2019 that was gazetted in November 2019 proposes 30 GW of new generation capacity to be connected to the system by 2030 (RSA Government, 2019). Currently, total generation capacity is 52.8 GW (Eskom, 2022).

7.2.2.1.6 National Development Plan 2030

The NDP is a plan which foresees that by 2030, South Africa will have a reliable and efficient energy sector providing energy at competitive rates. This will also consider social equity in terms of access to energy and environmental sustainability through reduced emissions. The NDP relied heavily on the Integrated Resource Plan (IRP) 2010–2030 (RSA Government, 2022).

7.2.2.1.7 Renewable Energy Independent Power Procurement Programme (REIPPPP)

The REIPPPP is South Africa's renewable energy public procurement programme and makes use of a tariff bidding process, which has recently completed its sixth bidding round, where each Independent Power Producer (IPP) submits their best tariff per project and technology. This mechanism promotes technology improvement and price efficiency (Eberhard et al. 2016).

Eskom, using its Single Buyer Office (SBO), then buys the energy produced via a power purchase agreement (PPA), over typically 20 years, at the bid tariffs per project. The South African Government also provides support for PPA payments through an Implementation Agreement with the DMRE.

7.2.2.2 Path to current state of the renewable energy sector

Whilst early energy white papers pointed towards energy supply from different resources, most notably renewable energy, the integrated energy and electricity plans developed in 2003 and 2011 respectively were the first attempt to formalise this and were ultimately the precursor to the IRP 2019, which outlines the rollout of various energy resources until 2030.

However, there was no action until 2010 when the first version of REIPPPP was implemented (Figure 7-1). The initial procurement mechanism for renewable energy in South Africa was the Renewable Energy Feed in Tariff (REFIT), subsequently replaced by REIPPPP, 2011. REIPPPP was carried out to facilitate the initial rollout of renewable energy in South Africa, mostly wind and solar (Creamer, 2012). Touted as a global standard for renewable energy rollout, over

the next 12 years from 2012 to 2022 in 6 bid windows (BW5), approximately 6.3 GW has been awarded and is already on the grid following what is defined by the IRP 2019 until 2030 (RSA Government, 2019). This is aligned with the NDP, which has as one of its key aims ensuring environmental sustainability and equitable transition to a low-carbon economy in South Africa (RSA Government, 2022). The national viewpoint on where centres for energy resources should be situated prior to 2011 aligns relatively well with what has been rolled out since then (Eaderlez-Taylor, 2011, IPPO, 2022).

In BW5, 2022, tariffs had a weighted average price of 47c / kWh, which injected R50 billion into the SA economy and created around 14 000 jobs (ESI, 2023). BW6, 2023, tariffs were primarily for Solar PV and jumped to 78c / kWh due to Covid-19 and the subsequent detrimental global supply chain issues. However, this is still below the baseload coal cost which is over 100c / kWh. In comparison, the average cost of the power procured in BW1, 2011, was R3.12 (in current terms) per kWh (IPPO, 2022).

Awarded REIPPPP projects generally have 6 months to attain financial close, 24 months to construct and can be online 30 months after the award. At present, the amount of wind, solar PV and concentrated solar power (CSP) capacity on the South African grid provides ~6.5% of South Africa's energy mix with another 26.3 GW of wind projected to be added to the grid by 2032 if grid capacity can facilitate this (CSIR, 2022b).

In the latest bidding round, BW6, the DMRE was procuring under REIPPPP:

- Initially 2 600 MW (1 000 MW Solar PV, 1 600 MW Wind according to the IRP)
- Amended to 5 200 MW (2 000 MW Solar PV, 3 200 MW Wind)
- Further amended to 4 200 MW (1 000 MW Solar PV, 3 200 MW Wind)

Actual submissions:

- Wind was slightly (1.3x) over-subscribed (3 200 MW available, 4 116.4 MW bid)
- Solar was notably (5.5x) oversubscribed (1 000 MW available, 5 550 MW bid)

Of the total of 4.2 GW allocated, only 1 GW of Solar PV was awarded. As a result, of the omission to award any wind projects, private PPAs have become more prominent and will be a focus area for the foreseeable future using wheeling. There has also been a notable shift towards the northern regions of South Africa due to strong grid capacity. However, here the wind resource is generally relatively low (WASA, 2023).

7.2.2.3 Current and future demand

Comparing the South African Energy Systems Power demand (instantaneous peak) versus six different possible scenarios for the demand forecast, the highest demand case is the high Transmission (TX) scenario. This scenario predicts a power demand in 2032 of 47 GW. The lowest demand case being the low TX scenario predicting a power demand in 2032 of 34 GW (Figure 7-1).

These forecasts have been revised down due to lack of generating capacity (which results in loadshedding), grid capacity, Covid-19 effects, and sustained economic downturn (Eskom, 2023b).

7.2.2.4 Infrastructure

Eskom generates more than 80% of South Africa's electricity, the majority of which comes from coal with the surplus being supplied by renewables, nuclear, gas and hydro (Ainger, 2022).

7.2.2.4.1 Transmission Grid

Generation has become the primary driver of Transmission Grid infrastructure development and thus the build out has become focused on connecting new generation to the grid (Eskom, 2023b).

Most of the large generation plants except for the Koeberg nuclear plant near Cape Town, South Africa's only nuclear power plant, reside in the Northern parts of the country and thus high voltage backbone Transmission Grids (400 kV and 765 kV) transport what is required to the load centres further southwards and along the coastlines. To facilitate the largescale rollout, a significant amount of grid powerlines, transformers, capacitors, and reactors are required (Eskom, 2023b).

The main reason provided for the minimal allocation of renewable energy capacity in REIPPPP BW6 was that grid capacity (which is outlined in the Eskom Generation Connection Capacity Assessment GCCA) deemed to be available ahead of BW6 had been subsequently reserved for projects being pursued by independent power producers (IPPs) that were being developed based on private offtakers¹⁵ power purchase agreements (PPAs).

During BW6, there had been no updates from Eskom after the GCCA, which guided bidders on what grid capacity was available, even when developers of private projects began reserving that available capacity. Furthermore, bidders under the REIPPPP are unable to make the financial commitments required to reserve grid capacity until they are named as Preferred Bidders, whereas developers of private projects face no such restriction. Thus, only a fraction of the BW6 allocation was awarded, and had a detrimental effect on renewable rollout confidence in future.

Going forward it is imperative that grid connection rules are fair and transparent and there also needs to be regular communication when circumstances change. To this end, SAWEA and the South African Photovoltaic Industry Association's (SAPVIA) Joint Task Team has maintained the importance of understanding, unpacking, and improving the Grid Queuing Rules now officially named the "Grid Capacity Allocation Rules" (GCAR) to ensure fair and transparent access to grid connections for all renewable energy projects.

Eskom has spent much time and effort in developing the rules to resolve the various issues that surfaced in BW6 of the REIPPPP regarding the allocation of grid capacity. In February 2023, Eskom engaged constructively with the Joint Task Team to share the latest draft of the rules and elaborate on the key principles that they were looking to incorporate into these rules prior to requesting an amendment to the South Africa Grid Code. As a result, these have morphed into the Interim

¹⁵ A private offtaker (as opposed to a public offtaker under a public procurement scheme) is an entity which contracts directly with an Independent Power Producer, via a private Power Purchase Agreements, for the production of energy supplied directly to that entity generally via wheeling agreements across the national transmission grid.

Grid Capacity Allocation Rules (IGCAR) which are now physically being implemented.

Accompanying these IGCAR, is Eskom's latest GCCA document (Eskom 2023) which provides an overview of what capacity each province must connect renewables to the grid. Although it has lost significant credibility since BW6, it does indicate capacity mainly in the Northern provinces with the Cape and Central provinces having no capacity at all. An addendum was released in February 2024 which made provision for curtailment and thus some additional grid capacity for variable renewable energy (VRE) generation plants.

An update from Eskom on the implementation of the Transmission Development Plan was produced in November 2023 and is geared towards adding the grid capacity required to unlock new generation capacity, including in the Cape provinces, where South Africa's best wind and solar resources are located (SAWEA, 2023a, 2023b, Eskom, 2023b). A viable accompanying mechanism to achieve this is to incentivise the private sector to carry out this build at utility scale and iteratively grow the grid while adding renewables to it.

7.2.2.4.2 Generation

South Africa's power generation is dominated by Eskom who has a theoretical baseload capacity at present of ~46.5 GW, however, there has been significant shortfall of this figure, resulting in near-constant load shedding across South Africa (see Section 2.2.4.3). Adding ~6.3 GW from IPP's increases the country's total power generation capacity to 52.8 GW (Eskom, 2022).

The plan to decommission the base load coal fired power stations situated predominantly in the North of South Africa is already being implemented. Energy production from these power stations will be halved by 2032 from ~30 GW down to ~16 GW of total capacity (RSA Government, 2019, Eskom, 2023b). In lieu of these decommissioned power plants, other sources of energy will continuously be added to the generation mix such as wind, open cycle gas turbines (OCGT), photovoltaic (PV), battery storage, hydro, concentrated solar plant (CSP) and biomass. The most notable additions are from wind, PV, OCGT and battery storage towards a projected maximum of 110 GW in 2035 (Eskom, 2023b).

7.2.2.4.3 Loadshedding

The notable loadshedding¹⁶ increase (Figure 7-1) in 2022 shows that Stage 6 loadshedding has been prominent for significantly longer in 2022 and for the first time since 2019. The statistics show continued decline in the energy availability factor (EAF¹⁷) of the entire Eskom fleet falling to an average of ~59% from ~62%, 2021 and 65%, 2020 (CSIR, 2022b). Each 1 GW of new renewable capacity can relieve approximately 1 level of load shedding. Therefore the ~6 GW of renewable energy from IPPs mitigates about 6 stages of loadshedding, avoiding catastrophic levels of loadshedding.

7.2.2.5 South Africa's Just Energy Transition (JET)

Taking into account the trajectory of the policy documentation and energy rollout programmes, coupled with the decommissioning of the base load coal fired power plants, the transmission grid build out driven by new generation and the major loadshedding difficulties, it is clear that an energy transition is in progress.

A group of international partners (IPG) including the USA, UK, Germany, France and the EU have welcomed and endorsed the Just Energy Transition (JET) of South Africa and the plan for investment in it. This plan aims to accelerate the greenhouse gas emission reduction and help South Africa achieve the Nationally Determined Contribution emissions goals (European Commission, 2022).

USD 9.3 billion is being put forward, mostly loans and grants, by the IPG to start the JET and is earmarked to be invested in green hydrogen, electric vehicles, and the energy sector. JET aims to protect those impacted by a transition from fossil fuel energy production with a total requirement of USD 98 billion in finance being required for the greater programme (European Commission, 2022). However, most of this finance is available as a debt instrument (loans), which add to already

¹⁶ Loadshedding of the electricity capacity in South Africa has become a common occurrence and is effectively the disruption of the electricity supply to avoid excessive load on utility scale generators.

¹⁷ The energy availability factor is the ratio of the energy that could have been produced by available capacity versus the energy that the complete capacity could have produced over a concurrent period.

high debt levels that aggravate economic challenges, especially due to high debt levels from the Covid-19 pandemic (Trisos et al., 2023).

Below is a summary infographic of the energy transition in South Africa over the past 25 years showing the possible risks and drivers going forward.

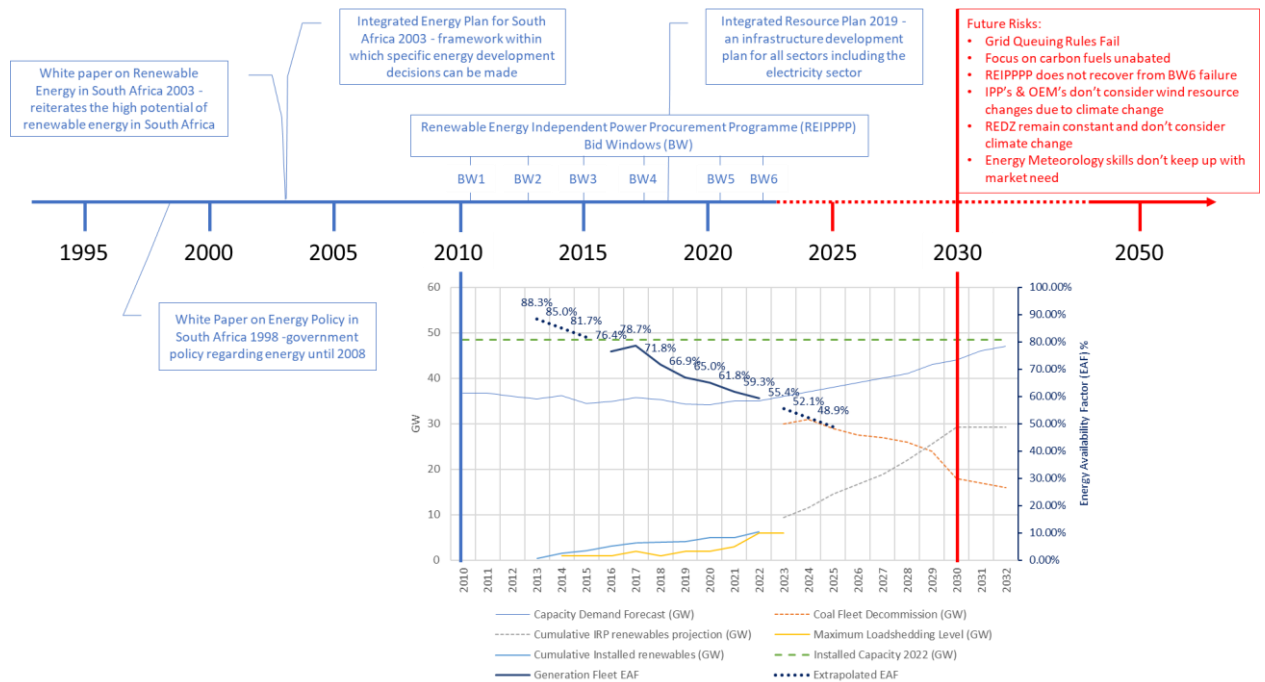


Figure 7-1: South Africa Energy Transition Infographic (RSA Government, 2019, Eskom, 2023b, CSIR, 2022b)

7.2.3 Climate change and wind energy in South Africa

The impact that climate change can have on wind resources is becoming more evident and especially important to understand given that South Africa's energy sector is poised to transition to more renewables in the mix.

7.2.3.1 Global picture

Man made global warming is currently increasing at an estimated 0.2°C per decade due to greenhouse gas emissions and the 1.5°C global warming level is likely to be exceeded in the early 2030s (IPCC, 2023).

7.2.3.2 Effect on South Africa

The sixth IPCC special report states that temperatures in the interior of South Africa are especially vulnerable to climate change and are increasing twice as fast as the global average due to it being warm, dry and water-stressed with sporadic drought (IPCC, 2021, CSIR, 2022a, Hoegh-Gulberg et al., 2018, Trisos et al., 2023, Engelbrecht, F. et al., 2018).

This has resulted in the frontal systems experienced mainly off the south coast of South Africa in winter, already being displaced pole-ward, increasing the potential for drought in the Cape Town region (Engelbrecht, C. et al., 2013). Thunderstorms are also increasing in frequency in Gauteng (Engelbrecht, C. et al., 2013). These changes are signs of the emergence of global tipping points in the earth's weather system. These tipping points increase the frequency, length, and strength of heat waves in South Africa (IPCC, 2021, Trisos et al., 2023).

It is important to develop improved understanding of regional tipping points and their potential in southern Africa. This will contribute towards developing climate change resilience and support a just transition towards a low-carbon economy. It will also facilitate an understanding of the impact of climate change on wind energy production and the development of risk mitigation and adaptation measures for the wind industry (IPCC, 2021).

7.2.4 Long term wind energy projections in the context of climate change

Given the state of the energy sector in South Africa and the energy transition that is being followed, novel research has recently been undertaken in South Africa to quantify the future vulnerability, variability, and systematic changes in energy production as it relates to Wind Energy Facilities (WEFs) in temporal and spatial dimensions, within the context of a changing climate (Landwehr et al., 2023a, Landwehr et al., 2023b) .

This research provides a methodology that uses the frequency changes of common synoptic patterns as long-term predictors of energy production over some

spatial area of interest. The methodology is tested in South Africa's Eastern Cape Province, which has been shown to have good wind energy potential.

The research found three synoptic patterns associated with the highest energy production are associated with the Atlantic Ocean high pressure system with a centre near 30 °S, ridging behind a mid-latitude cyclone passing to the south of the country. For all three synoptic states, the net result is pronounced southwesterly flow over the Eastern Cape highlighting the importance of strong southwesterlies for wind energy generation in the region (Landwehr et al., 2023a) .

The synoptic pattern associated with the lowest energy generation potential for the Eastern Cape represents mid-latitude cyclones with a more poleward and eastward location and a weak ridging high pressure with centre at about 35°S. Pressure gradients are consequently weak over the Eastern Cape, and wind energy production is low.

Future projections of wind characteristics in this area, based on a nine ensemble of CMIP6 GCM projections validated by ERA5 reanalysis data, indicate an average decrease in wind energy generation between 2020 and 2090. This has an impact on the overall capability for wind energy generation and the internal rate of return for associated project business cases (Landwehr et al., 2023b).

The likely cause of this circulation change is the poleward expansion of the descending limb of the Hadley circulation. This (1) displaces frontal system southward together with the high-pressure systems off the southwest coast associated with high energy production and (2) the centre of the Kalahari High over the interior shifts southward towards the study region, recognising that winds associated with high pressures are weakest at the centre of the system and strongest at the edges (Landwehr et al., 2023b).

7.3 Climate change risk assessment and mitigation

Lopez from Climate Scale (2023) presented a proposed methodology for standardising climate risk reporting at Wind Europe 2023. According to Lopez, climate risk is quantified according to temperature, wind, water and solid mass with

a key consideration being the uncertainty associated with each of these aspects. Intrinsic to all of these is the economic aspects. The following is a first pass risk assessment with mitigation measures for areas of the wind energy sector that will be impacted by climate change.

7.3.1 Long Term economic risk and mitigation

Looking at the economic risk of this P50 energy production change, quantified by Landwehr et al., 2023, a 140 MW WEF IRR could reduce by ~ 0.7% over the lifetime of the WEF in the study specific spatial area (Landwehr et al., 2023b).

To mitigate this risk, the minimum IRR acceptable IRR can be increased to negate projects that would breach this. The P75 energy production can also be used to test the sensitivity of financial models particularly for the lender's scenarios. Furthermore, climate change impact on the P50 can be incorporated into the loss regime for the energy production.

7.3.2 Renewable Energy Development Zones (REDZ)

Geographical areas created by the Department of Forestry, Fisheries, and the Environment (DFFE), the REDZ, have been selected for many reasons, such as resource, grid proximity, land availability (SAWEA, 2021). The purpose is to streamline and attract wind and solar PV development in focused zones facilitating investment and enabling higher levels of renewable energy roll out (SAWEA, 2021).

These zones are based upon information indicating where the best wind and solar resources present themselves in conjunction with proximity to available capacity on the electricity grid. For this reason, forecasting of where the wind resource will be favourable or unfavourable in the coming decades will be a useful input to assist in the defining of the future REDZ.

Given the spatial area that was investigated by Landwehr et al., 2023a and 2023b, with the risk that wind energy production will decline in these areas for PPAs

between 2020 and 2080, it would be prudent to mitigate this risk by shifting the wind REDZ further up the East or Southwest coasts pending the results of a similar study for that region. This is further supported by the stronger grid on the East coast as per the TDP.

7.3.3 WEF siting by Independent Power Producers (IPPs)

IPPs are constantly searching for new WEF sites via a process called 'greenfielding'. As the REIPPP programme enters its seventh bidding window, this activity is gaining momentum since majority of the well-developed projects, in project pipelines for up to 5 years, have now been bid and anything with net capacity factors above 40% has generally gained a PPA. A risk thus emerges that viable sites are running out.

If 40% is the benchmark going forward, the results of Landwehr et al., 2023a and 2023b could suggest that for PPAs ranging from 2020 to 2080 it would be prudent to rerun the methodology outlined in (Landwehr et al., 2023a) and (Landwehr et al., 2023b) for larger areas to identify areas that will have possible increase in wind energy production.

7.3.4 Original Equipment Manufacturers (OEMs)

In a changing climate, the mechanical loading and temperature impacts on WTGs is a risk that must be considered. Using the methodology outlined in (Landwehr et al., 2023a) and (Landwehr et al., 2023b), synoptic systems that are identified to occur more frequently can be used to define the correct WTG components that may be necessary in the future. For example, increased dry hot conditions might require nacelles, towers and blades that take this into account. Additionally, power curves may need to be adapted to consider high temperature de-rating and thus also adding to the negative loss regime impact in the energy production estimations.

To mitigate this risk, the results of Landwehr et al., 2023a and 2023b could suggest that going forward, it could be sensible to select WTGs more suitable to lower average annual wind speeds.

7.3.5 Integrated energy and resource plans

Currently, the IRP 2019, which stipulates the rollout of various energy production plants until 2030, shows a clear focus on wind with the addition of wind power at 1.6 GW per year. There is obviously a risk that this could be an over or under allocation.

A mitigation for this risk would be to run the methodology proposed by Landwehr et al., 2023, for the whole country and by doing so can, in advance, guide the IRP's allocation in a more educated fashion going forward.

7.3.6 Offshore wind

Taking into account the grid build out provided by the Eskom TDP which outlines the proposed grid infrastructure to be built by the utility over the next 10 years, it is clear that strengthening is going to occur in the Cape provinces, areas that are good for renewable energy rollout. The northern regions of South Africa are also being marketed to attract renewables on account of the decommissioning of the coal power stations which leave in their wake an exceptional grid connection business case for IPPs.

Taking these two factors into account, there could be sufficient grid capacity in these areas for the next several decades which poses an opportunity rather than a risk for WEFs.

By rolling out the methodology from (Landwehr et al., 2023a) and (Landwehr et al., 2023b) for the rest of the country, with the results allowing the South African wind energy sector to capitalise on this opportunity by providing an indication of when offshore wind could present a good business case sooner.

7.3.7 Development of skills

This study undertaken in (Landwehr et al., 2023a) and (Landwehr et al., 2023b) illustrates the nexus between Renewable Energy Yield Analysis and Atmospheric Science (together termed Energy Meteorology) (University of Oldenburg, 2024), that requires skills not readily available in South Africa. However, the transition to renewable energy is highlighting the risk that these skills are in short demand. They include:

- Annual energy calculations
- Understanding of suitable OEM technology for a particular site
- Familiarity with climate datasets such as ERA5 and software such as CDO and Python
- A suitable understanding of dominant weather systems affecting a spatial focus area
- Experience in identifying suitable grid connection positions and forecasting the transmission grid rollout.
- Experience in selecting and creating ensembles of GCMs and using them to develop energy production projections dependent on climate change.

This is a diverse skillset which is not taught holistically as a single course or degree in South Africa universities.

To mitigate this risk, a relevant curriculum must be developed in South Africa that addresses the themes listed above and rolled out via internships, graduate recruitment, and specialist course delivery at participating universities.

7.4 Practical execution

Given the state of South Africa's energy sector, there is a clear need to develop wind energy risk and mitigation capability to sustain this energy future. In the light

of this, the following is a practical blueprint proposal for how to materialise such capabilities.

7.4.1 Basic User Requirement Specification

The background software engine to provide the required outputs should be able to:

- Operate on a secure cloud-first strategy to automatically import measured wind energy generation plant production data where available
- Produce wind energy projections forecasts at an aggregated national level at all timescales
- Produce wind energy projections at a disaggregated generation plant level at all timescales
- Provide error evaluation and model validation functionality by using metrics such as MAE and RMSE
- Provide comprehensive data analysis and reporting
- Enable a wind energy projection workflow mechanism that includes change monitoring and forecast approval
- Provide suitably capable user interfaces, hardware and networking infrastructure to handle data transfer and model operation

7.4.2 Technical requirements

Using the compute resources required by Landwehr et al., (2023) as a proxy for what type of High-Performance Computing is required to implement the proposed wind energy projection capability, we estimate the computational resources that would be required for a long-term analysis baseline study of projected changes in long term wind energy production in the Eastern Cape Province of South Africa (Table 7-1).

Table 7-1: Computing power used for long term analysis baseline study

	Data Preparation	SOM Training	Synoptic Pattern Generation	Correlations
No of computations estimate	50 000	400 000	4 800 000	126 000 000
Computations per second	20	30	2	4
CPU Specification	intel core i7 2.8 GHz Core	intel core i7 2.8 GHz Core	intel core i7 2.8 GHz Core	intel core i7 2.8 GHz Core
RAM	24 GB	24 GB	24 GB	24 GB
Total Core Hours (hrs)	1	4	667	8750

Ultimately it is envisaged that this method can be run in much shorter timescales for whole countries with overlapping spatial areas to provide much higher resolution indications of wind energy fluctuations in the long term.

Considering the case where the number of GCMs is increased by a factor of ten and the spatial area increased to a country size of fifty composite spatial areas at the same speed, this would result in 4.3 million core hours (Table 7-2).

Table 7-2: Computing power used for long term analysis and extension of study

	Data Preparation	SOM Training	Synoptic Pattern Generation	Correlations
No of computations estimate	25 million	200 million	2 400 million	63 000 million
Computations per second	20	30	2	4
CPU Specification	intel core i7 2.8 GHz Core	intel core i7 2.8 GHz Core	intel core i7 2.8 GHz Core	intel core i7 2.8 GHz Core
RAM	24 GB	24 GB	24 GB	24 GB
Total Core Hours (hrs)	348	1851	333 500	4 375 000

With the aid of faster computation power, these computations could be churned out much quicker. Considering the University of the Witwatersrand's single Stampede Rack which comprises of 40 nodes and ultimately 640 Cores of the Xeon E5-2680 2.7 GHz processors, it can be assumed that this baseline study can be performed 640 times faster. Thus, as per Table 7-3 below, the original baseline study would take approximately half a day with the extended study being reduced to 7361 core hours.

Table 7-3: Improved Computing power used for long term analysis and extension of study

	Data Preparation	SOM Training	Synoptic Pattern Generation	Correlations
No of computations estimate	25 million	200 million	2 400 million	63 000 million
Computations per second	20	30	2	4
CPU Specification	intel core i7 2.8 GHz Core	intel core i7 2.8 GHz Core	intel core i7 2.8 GHz Core	intel core i7 2.8 GHz Core
RAM	24 GB	24 GB	24 GB	24 GB
Total Core Hours (hrs)	348	1851	333 500	4 375 000

As a result of this analysis, the sizing requirement will be in the order of at least one full rack of a Stampede or equivalent High-Performance Computer. Conceptually the architecture would resemble Figure 7-2.

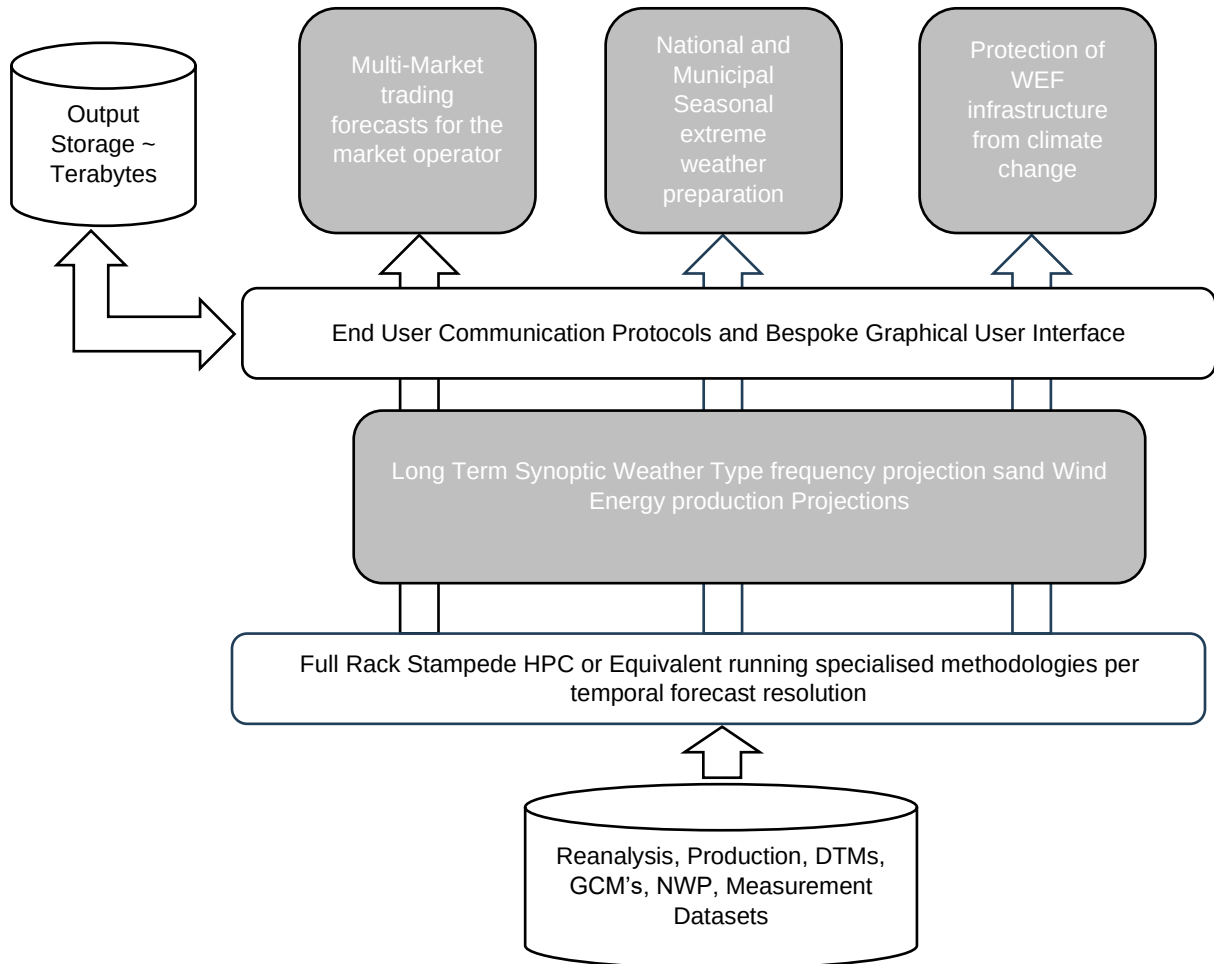


Figure 7-2 Conceptual Architecture

7.5 Conclusion

South Africa's energy sector has faced severe headwinds in recent years and will continue to do so for the next decade. This is evidenced through loadshedding and the need to decommission the aging coal fire power station fleet. Furthermore, the stunting of the public renewable energy procurement process in 2022 was a low point for the industry. However, the latest Eskom TDP does highlight that over the next 10 years, the intention is to heavily build out the grid to facilitate the projected growth in renewables outlined in the latest IRP. A viable accompanying mechanism to achieve this would be to incentivise this build out of the grid at utility scale with private investment and iteratively grow the grid while adding renewables to it.

To stabilise and sustain a future extensive wind energy heavy power system in South Africa in a changing climate, this paper has shown that it is necessary to understand how WEFs will perform in the long term. Furthermore, understanding how global warming changes the frequency, intensity and duration of extreme weather events and how the renewable energy resources may change in the longer term is important for all industry stakeholders. It is proposed that the new methodologies described in (Landwehr et al., 2023a), (Landwehr et al., 2023b) be expanded to grow the countries capability to assess and mitigate climate change risk impacting WEFs.

7.6 Author contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Greg Landwehr, and supported by Francois Engelbrecht and Chris Lennard. The first draft of the manuscript was written by Greg Landwehr and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

7.7 Declarations

7.7.1 *Funding*

Funding: This work was supported by the National Research Foundation of South Africa through its Earth System Science Research Programme, Grant 118598.

7.7.2 *Conflict of Interest Statement*

All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

7.7.3 *Data Availability Statement*

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

We acknowledge the World Climate Research Programme, which, through its Working Group on Coupled Modelling, coordinated and promoted CMIP6. We thank the climate modelling groups for producing and making available their model output, the Earth System Grid Federation (ESGF) for archiving the data and providing access, and the multiple funding agencies who support CMIP6 and ESGF.

8. CHAPTER 8: DISCUSSION

Due to the abundance of wind and solar renewable energy resources across South Africa, and the comparative low cost of installation and operation of wind and solar energy infrastructure, it is inevitable that the country's dependence on fossil fuels for energy will decline in the future. This transition from an overwhelming reliance on coal to a system based on variable renewable energy will be further accelerated by the growing concern over high levels of air pollution in the areas where fossil fuel power plants exist, and the contribution of emissions to climate change and its impacts.

Global electricity generation capacity at present is ~7 Terawatts. According to IRENA's reference case forecast, which reflects changes in the energy system under current policies, this could reach ~15 Terawatts by 2050. It is very likely that contributions from renewable energy will outstrip non-renewable energy from around 2030 onwards. In terms of growth, measured as a percentage of the total global energy production, onshore wind is projected to provide 25% of the total generation in this scenario.

Within South Africa, this transition to sustainable renewable energy is possible if steps are taken to achieve this via public and private procurement mechanisms. Furthermore, to achieve the long-term sustainability of the energy sector, it will become increasingly important to accurately predict how variable renewable energy production will be impacted, temporally and spatially, by a changing climate.

At a practical level, developing wind energy facilities entails a complex array of activities involving land acquisition, permitting, energy yield analysis, construction, and once constructed, operating the facility during its twenty-to-thirty-year life span. The life span of such a development intrinsically implies that it will experience climate change. However, very little research and related modelling have been undertaken in South Africa to quantify future variability and systematic changes in the wind resource as it relates to wind energy production in temporal and spatial dimensions. Moreover, how South Africa's wind energy potential relates to the occurrence of specific synoptic weather types has not yet been quantified.

Work on long-term future projections of wind energy, particularly using GCMs, has been limited in South Africa's wind resource rich areas such as the Eastern Cape Province. Although similar studies have been conducted for other parameters such as temperature and rainfall (Engelbrecht, C. et al., 2014), no work has been done to quantify wind energy yield potential of the Eastern Cape Province of South Africa as it relates to the accompanying synoptic weather systems of the region. Some work has been conducted using SOMs however, this research focuses on the variability of wind speeds (van Aarde et al., 2023) and stops short of correlating this with wind energy potential.

This thesis has, in Paper 1 (Chapter 5) presented a methodology to quantify the present-day wind climatology and associated net capacity factors of WEFs in South Africa's Eastern Cape Province using observational data sets and detailed regional climate modelling. The foundation for Paper 1 (Chapter 5) is the long-term meteorological wind speed measurement data available for four sites in the Eastern Cape from WASA. This data was drawn from the Wind Atlas of South Africa (CSIR, 2019) and enabled the calculation of annual and seasonal energy production at four representative locations in the Eastern Cape. At each of the four sites, annual average wind speeds vary between 7 and 8 m/s, indicating a potentially high wind resource (CSIR, 2019). The energy yield analysis reveals the importance of winter as the season with the highest energy potential, not a surprising result, given the northeast passage of mid-latitude cyclones over the Southern Ocean. Generally, energy production is the highest around midday and the afternoon, likely because the ocean temperature gradient is then at its steepest, strengthening pressure gradients and winds. A thirty-five node SOM was generated to identify the prevailing circulation types of the Eastern Cape, using ERA5 reanalysis data at 6-hourly resolution, and mapping six-hourly resolution wind energy production onto the SOM. This thesis is hereby the first to quantify the wind energy meteorology of the Eastern Cape, by objectively exploring the wind energy production potential of different synoptic weather types. The SOM analysis reveals that the synoptic-circulation pattern with the highest energy potential for the Eastern Cape is the Atlantic Ocean ridging high with its centre at about 30 °S, behind a northward displaced mid-latitude cyclone. This results in steep pressure gradients and predominantly south-westerly winds over the Eastern Cape.

However, when mid-latitude cyclones pass over the Southern Ocean further to the south, and the Atlantic Ocean High ridges with its centre further to the south at about 35 °S, pressure gradients and energy production is weakest. These results are consistent with the identification of synoptic systems bringing high winds to South Africa in winter completed by Preston-Whyte (1988), (Tyson et al., 1988). These include the ridging anticyclones and coastal lows and of course the mid-latitude cyclones (Tyson et al., 1988).

The methodology developed here, linking wind energy production to archetypal synoptic weather types identified by the SOM, is promising and can be used for the projection of energy production in the long-term using GCMs whose spatial resolution is relatively low.

At present, a universally applicable methodology for producing detailed long-term projections of how the wind energy production might change in the Eastern Cape Province of South Africa as a result of changing climate has not been developed. A CMIP6 GCM ensemble method to investigate the long-term change in frequency of high wind energy producing synoptic weather systems is likely to produce reliable results based on similar studies that project rainfall and temperature changes (Engelbrecht, C. et al., 2013, Engelbrecht, C. et al., 2014, Engelbrecht, F. et al., 2009). Furthermore, although done in other regions, no quantification of the impact on IRR for WEFs has been conducted.

This thesis has developed, in Paper 2 (Chapter 6), detailed projections of how the wind resource in the Eastern Cape will change over time under different mitigation scenarios. The trained SOM results from Paper 1 (Chapter 5) were applied to an ensemble of GCMs to project future wind energy potential through the lens of projected changes in synoptic weather type frequencies. When projecting the frequency of high wind energy yielding synoptic weather types, it is shown that there is a decrease in their frequency at the chosen warming temperature thresholds in the spatial focus area. This has an impact on the overall capability for wind energy production. Possible commercial impact indicates an IRR decline in PPA periods 2021-2080 at an average of 0.7% for the full 20-year lifetime of the WEF. This change is likely a result of poleward displacement of frontal systems due to an expanding descending limb of the Hadley circulation and more extensive

high-pressure system over the country (Archer et al., 2018, Engelbrecht, F. et al., 2019).

These GCM specific results are aligned with a similar study carried out in 2023 where three sites using three socioeconomic pathways also for an ensemble of CMIP6 GCMs were considered showing a maximum decline in the IRR over the lifetime of the WEF from between 0.1 to 0.6% (Gebraad et al., 2023). The sites considered were closer to the Equator in Brazil and Europe and slightly higher IRR impacts are projected due to the lower latitudes of this study (Gebraad et al., 2023).

A practical disadvantage of this approach is that only a few CMIP6 modelling groups have made available six-hourly geopotential fields, so that the size of the multi-model ensemble we use in the thesis to project changes in future energy generation is relatively small. Larger available ensembles of mean sea-level pressure (MSLP) can be used to approximate in the same manner, near-surface wind fields for wind farms close to the coast (WCRP, 2023). However, being a diagnostic variable derived from prognostic variables, mean sea-level pressure patterns will be a less ideal for approximating wind patterns over the South African plateau (Engelbrecht, Lennard, 2024). Geopotential height is thus the chosen parameter for this thesis and is a standard output from GCMs at different pressure levels. Under geostrophic balance it defines the wind-field at synoptic weather-system spatial scales. Over South Africa's Eastern Cape, the 1000 hPa geopotential height, a GCM prognostic variable, has the advantage of providing a reasonable approximation of the height at which the wind farms are located (Engelbrecht, 2024). Deeper into the interior, the 850 hPa geopotential height is a better approximation to describe near-surface winds over the plateau (Engelbrecht, 2024). Further research will use MSLP in parallel to the geopotential height and expand the study to analyse projected wind energy production changes in different parts of South Africa as well as globally.

Renewable energy installations are growing globally and locally in South Africa (IEA, 2018, IEA, 2022, IEA, 2023) and thus predicting the performance of these variable forms of energy in a changing climate is of increasing importance. Risk mitigation of climate change impacts on renewable energy plants must be

considered for safeguarding South Africa's renewable energy future but are not, to date, being sufficiently outlined using scientific methods according to the literature.

The spin off from the novel research in Paper 1 (Chapter 5) and Paper 2 (Chapter 6) is Paper 3 (Chapter 7), which presents the headwinds facing South Africa in forging a path towards a renewable energy future. This is evidenced through loadshedding and the need to decommission the aging coal fire power station fleet. Furthermore, the stunting of the public renewable energy procurement process in 2022 was a low point for the industry. However, the latest Eskom TDP does highlight that over the next 10 years, the intention is to heavily build out the grid to facilitate the projected growth in renewables outlined in the latest IRP. A viable accompanying mechanism to achieve this would be to incentivise this build out of the grid at utility scale with private investment and iteratively grow the grid while adding renewables to it. Paper 3 discusses the major areas which this research will impact such as defining REDZ, better informing WEF positioning and WTG selection and improving EYAs by incorporating climate change losses. Furthermore, it casts a vision for building on these methodologies to facilitate the future establishment of risk assessment and mitigation measures to adapt to climate change issues impacting the wind energy industry in South Africa.

9. CHAPTER 9: CONCLUSION

The share of the total installed power capacity held by wind energy facilities in South Africa will increase notably by the late 2020s (RSA Government, 2019). For South Africa to pursue a transition out of its heavy dependence on coal, it needs to increasingly invest in the country's rich resources of wind energy. The Eastern Cape province exhibits a favourable wind resource which can be exploited towards expediting such a transition. The variable nature of renewable energy requires the tools to accurately predict its variable wind energy production in the long-term and facilitate the future proofing of renewable energy generation plants in a changing climate.

The aim of this research has been to assess how a changing climate may impact the wind energy potential in South Africa and develop a methodology to accomplish this at scale and over the long-term. This thesis presents a newly developed methodology that links commonly occurring synoptic weather types to the wind energy production of WEFs in South Africa's Eastern Cape Province. Furthermore, a universally applicable methodology for producing detailed long-term wind energy projections from GCMs for the Eastern Cape Province has also been developed and presented in this thesis.

Results show a decline in wind energy production because of the poleward expansion of the descending limb of the Hadley circulation which shifts these synoptic systems southwards. This (1) displaces frontal system southward together with the high-pressure systems off the southwest coast linked with producing high wind energy and (2) shifts the centre of the Kalahari High over the interior southward towards the study region, recognising that winds associated with high pressures are weakest at the centre of the system and strongest at the edges. The economic impact of the change in P50 wind energy production level on wind energy facilities is investigated and shows that the internal rate of return declines over the lifetime of the wind energy facility. Future work will involve extending these projections to the whole of South Africa.

Finally, this thesis identifies contexts within the South African wind industry that will be impacted by these wind energy projections and in turn suggests risk

mitigation measures for adaptation to climate change impacts on the wind energy sector in South Africa.

The looming decommissioning of the Eskom coal fire power plants, grid constraints, the knock-on effects of extended high impact load shedding and aging nature of Koeberg (South Africa's only nuclear power plant) highlights the urgent need for roll out of wind and solar renewable energy generation facilities in South Africa. This thesis provides methodologies, fit for purpose, to understand the temporal and spatial impacts of climate change on wind energy facilities and their energy production thus, securing their sustainability in the long term.

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APPENDIX A: Reshaping netCDF for use in SOMPAK ©

```
#!/usr/bin/env python
# coding: utf-8

import numpy as np
import xarray as xr
np.set_printoptions(suppress=True)

# SOM configuration is 1-D map with size from 35 Nodes
# input file in netcdf format geopotential height for 1979-2019 reduced envelope -
# 30S, -35S and 20E to 30E
ifile = '2010_2019_gph_EcAaSubtracted_EcArea.nc'
# Geopotential height
var = 'z'

# reading and processing input data
d1 = xr.open_dataset(ifile)[var]
#print(d1)

# amending the longitude values if in the eastern hemisphere
d1.longitude.values[d1.longitude.values < 0] =
d1.longitude.values[d1.longitude.values < 0] + 360

# assigning lat and long to internal variables
lat2d, lon2d = d1['latitude'].values, d1['longitude'].values

# Setting up the Ouput directories
key = 'Sompak'
odir0 = 'Sompak/'+key+'/'
d3 = d1
```

```

odir = 'Sompak/'+key + '/'
#if not os.path.exists(odir): os.makedirs(odir)
#d3.to_netcdf('Sompak/'+key+'/origdata.nc') # write original data for latter checking
if necessary

# still in 2d format i.e. lat x long
iput2d = d3.values
iput2d = np.flip(iput2d,1)
# reshapes the data for 1 dimensional SOM input i.e. 861 values in a line top to
bottom
iput1d = iput2d.reshape(iput2d.shape[0],-1)
# convert to geopotential height and subtract area average from the start of the
energy data
#write the .dat file for SOMPAK
with open(odir + 'sompak_matrix.dat', 'a') as f:
    for i in range (0,14003):
        tempiput = iput1d[i]
        tempiput = np.round(tempiput,3)
        tempiput = str(tempiput)
        #print(tempiput)
        tempiput = tempiput.replace("\n", "")
        tempiput = tempiput.replace("\r", "")
        tempiput = tempiput.replace(" ", ",")
        tempiput = tempiput.replace("[", "")
        tempiput = tempiput.replace("]", "")
        tempiput = tempiput.replace(",,", " ")
        tempiput = tempiput.replace(",,", " ")
        tempiput = tempiput.replace(",,", " ")
        f.write(tempiput + '\n')
    print(str(i))

#y = iput1d.reshape(14608,iput2d.shape[-2],iput2d.shape[-1])

```

```
#do = xr.Dataset()
#do[var] = (['n','lat', 'lon'], y)
#do.coords['lat'] = lat2d
#do.coords['lon'] = lon2d
#ofile = odir + 'SOM_READY.nc'
#do.to_netcdf(ofile)
#do.close()
```

APPENDIX B: Synoptic Type Creation using trained SOM BMUs

Example regridding GCMs using CDO for a particular:

```
gridtype=lonlat  
xsize=360  
ysize=180  
xfirst=-179.5  
xinc=1  
yfirst=-89.5  
yinc=1
```

```
cdo remapbil,mygrid zg1000_6hrPlev_NorESM2-  
LM_ssp370_r1i1p1f1_gn_205101010300-206012312100.nc  
zg1000_6hrPlev_NorESM2-LM_ssp370_r1i1p1f1_gn_205101010300-  
206012312100_1degree.nc
```

Example of slicing out the spatial area of interest:

```
cdo sellonlatbox,0,50,-10,-50 zg1000_6hrPlev_NorESM2-  
LM_ssp370_r1i1p1f1_gn_205101010300-206012312100_1degree.nc  
zg1000_6hrPlev_NorESM2-LM_ssp370_r1i1p1f1_gn_205101010300-  
206012312100_1degree_sellonlatbox.nc
```

```
cdo sellonlatbox,20,30,-30,-35 zg1000_6hrPlev_NorESM2-  
LM_ssp370_r1i1p1f1_gn_205101010300-206012312100_1degree.nc  
zg1000_6hrPlev_NorESM2-LM_ssp370_r1i1p1f1_gn_205101010300-  
206012312100_1degree_sellonlatboxECArea.nc
```

Example of extracting each timestep for area averaging:

```
cdo -seltimestep,1 zg1000_6hrPlev_NorESM2-  
LM_ssp370_r1i1p1f1_gn_205101010300-  
206012312100_1degree_sellonlatboxECArea.nc  
ECTimesteps_2051_2060/TS1_zg1000_6hrPlev_NorESM2-
```

LM_ssp370_r1i1p1f1_gn_205101010300-
206012312100_1degree_sellonlatbox_ECAverage.nc

Example of extracting greater spatial area for each timestamp:

```
cdo subc,117.73 Timesteps_2051_2060/TS1_zg1000_6hrPlev_NorESM2-  
LM_ssp370_r1i1p1f1_gn_205101010300-  
206012312100_1degree_sellonlatbox.nc  
ECTimesteps_2051_2060/subc/TS1_zg1000_6hrPlev_NorESM2-  
LM_ssp370_r1i1p1f1_gn_205101010300-  
206012312100_1degree_sellonlatbox_ECSubc.nc
```

Example of creating the average of all timesteps that correlate to a single SOM node (node 1 in this case):

```
cdo ensmean N1_* node_1.nc
```

APPENDIX C: Correlation and Averaging of Timestep pattern to SOM Node

Pattern

(Code was run for 9 GCMs for 90 years [2010 to 2100] at 3-hour resolution = 2.1 million iterations, each compared to 35 nodes resulting in 73.5 million computational comparisons)

```
#!/usr/bin/env python
```

```
# coding: utf-8
```

```
import numpy as np
```

```
import xarray as xr
```

```
from cdo import *
```

```
import os
```

```
from datetime import datetime
```

```
TSAverages=[]
```

```
maxPCC=-1
```

```
node=1
```

```
nodePCC=[]
```

```
allPCC=[]
```

```
allTimestamps=[]
```

```
GCMName = 'zg1000_6hrPlev_NorESM2-
```

```
LM_historical_r1i1p1f1_gn_201001010300-201412312100'
```

```
GCMDecade = '2010_2014'
```

```
timestampStart = 1
```

```
timestampEnd = 14601
```

```
cdo = Cdo()
```

```
np.set_printoptions(suppress=True)
```

```
os.mkdir("Timesteps_"+str(GCMDecade))
```

```

os.mkdir("ECTimesteps_"+str(GCMDDecade))

# Bilinear interpolation to mygrid
cdo.remapbil("mygrid",input=str(GCMName)+".nc",
output=str(GCMName)+"_1degree.nc")

# Sellonlatbox
cdo.sellonlatbox('0,50,-10,-50', input=str(GCMName)+"_1degree.nc",
output=str(GCMName)+"_1degree_sellonlatbox.nc")
cdo.sellonlatbox('20,30,-30,-35', input=str(GCMName)+"_1degree.nc",
output=str(GCMName)+"_1degree_sellonlatboxECArea.nc")

for timestamp in range (timestampStart,TimestampEnd):
    print("TSTP: "+str(timestamp))
    print(datetime.now().strftime('%Y-%m-%d %H:%M:%S'))
    cdo.seltimestep(timestamp,
input=str(GCMName)+"_1degree_sellonlatbox.nc", output
="Timesteps_"+str(GCMDDecade)+"/TS"+str(timestamp)+"_"+str(GCMName)+"_1
degree_sellonlatbox.nc")
    cdo.seltimestep(timestamp,
input=str(GCMName)+"_1degree_sellonlatboxECArea.nc", output
="ECTimesteps_"+str(GCMDDecade)+"/TS"+str(timestamp)+"_"+str(GCMName)+"
_1degree_sellonlatbox_ECAverage.nc")

    GCMifile =
'ECTimesteps_'+GCMDDecade+'/'+'TS'+str(timestamp)+'_'+str(GCMName)+'_1degr
ee_sellonlatbox_ECAverage.nc'
    var2 = 'zg1000'
    GCMtimestamp = xr.open_dataset(GCMifile)[var2]
    # still in 2d format i.e. lat x long
    iput2d = GCMtimestamp.values
    # reshapes the data for 1 dimensional SOM input i.e. 861 values in a line top
to bottom

```

```

input1d = input2d.reshape(input2d.shape[0],-1)
tempiput = input1d[0]
tempiput = np.mean(tempiput)
tempiput = np.round(tempiput,3)
tempiput = str(tempiput)
print('AVG###'+tempiput)

#Subtract average from greater spatial area
cdo.subc(tempiput,
input="Timesteps_"+str(GCMDecade)+"/TS"+str(timestamp)+"_"+str(GCMName)
+"_1degree_sellonlatbox.nc",
output="Timesteps_"+str(GCMDecade)+"/TS"+str(timestamp)+"_"+str(GCMName)
+"_1degree_sellonlatbox_ECSbc.nc")

GCMifile =
"Timesteps_"+str(GCMDecade)+"/TS"+str(timestamp)+"_"+str(GCMName)+"_1d
egree_sellonlatbox_ECSbc.nc"
var2 = 'zg1000'
GCMtimestamp = xr.open_dataset(GCMifile)[var2]

for i in range (0,35):
    ifile = 'Original SOM
Nodes/Run8_SOMPAK_netcdf_Result_EcAaSubtracted_NodeAverage/node_'+s
tr(i+1)+'_regrid_1degree_sellonlatbox_gph_100hpa.nc'
    var = 'z'
    tempNode = xr.open_dataset(ifile)[var]
    tmp = xr.corr(tempNode[0],GCMtimestamp[0])
    nodePCC.append(float(str(tmp)[28:32]))

k=0
for j in nodePCC:
    k = k+1
    if j > maxPCC:

```

```

        maxPCC = j
        node = k

    print('Maximum Correlation is '+str(maxPCC)+' with node '+ str(node))

    allPCC.append(node)

    nodePCC.clear()
    maxPCC = -1
    node = 1

with open(str(GCMDecade)+'_allPCC.txt', 'w') as f:
    f.write(str(allPCC))
print(allPCC)

```

APPENDIX D: Sample of Meteorological Mast Data Output

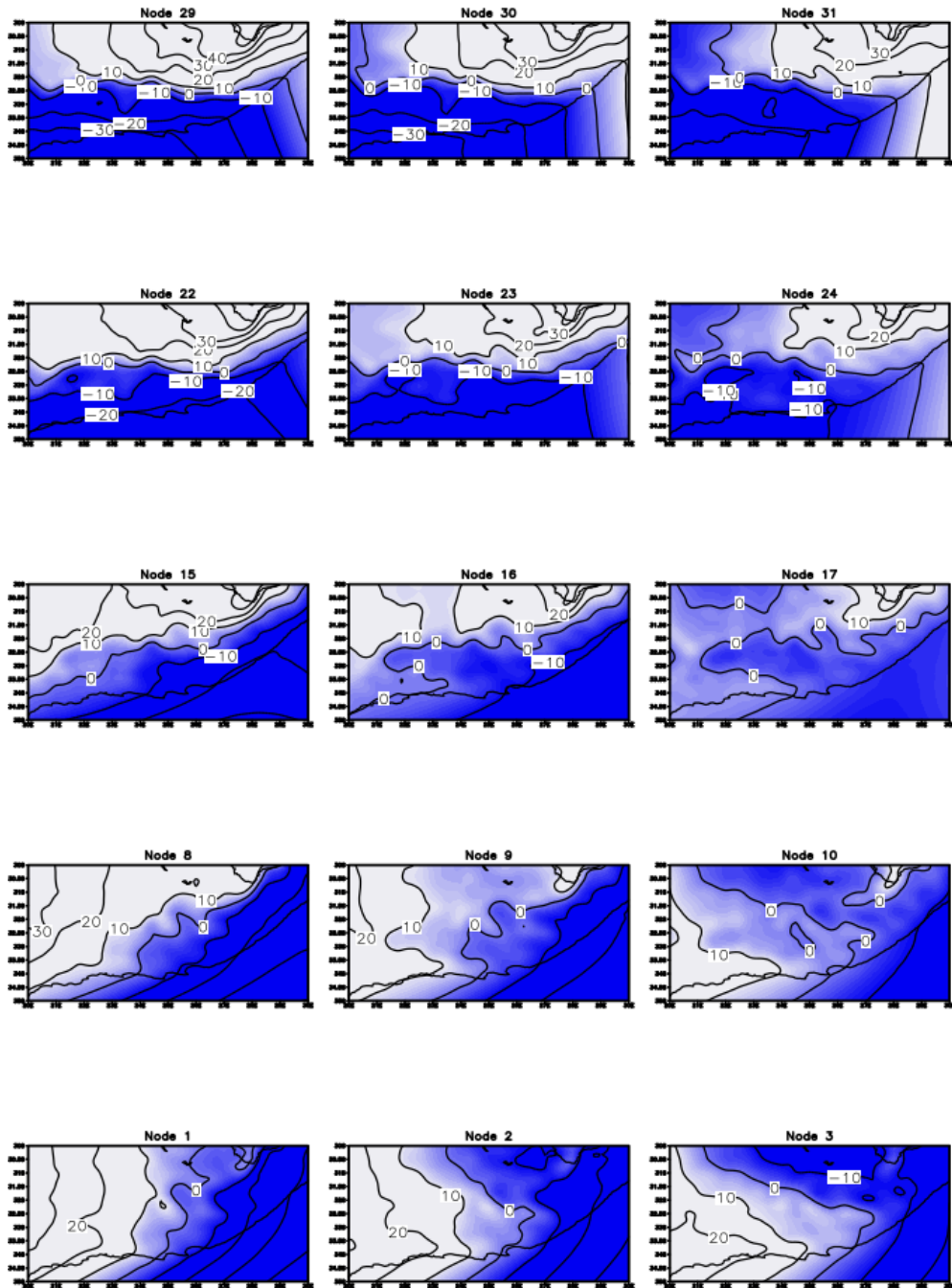
[illegible]

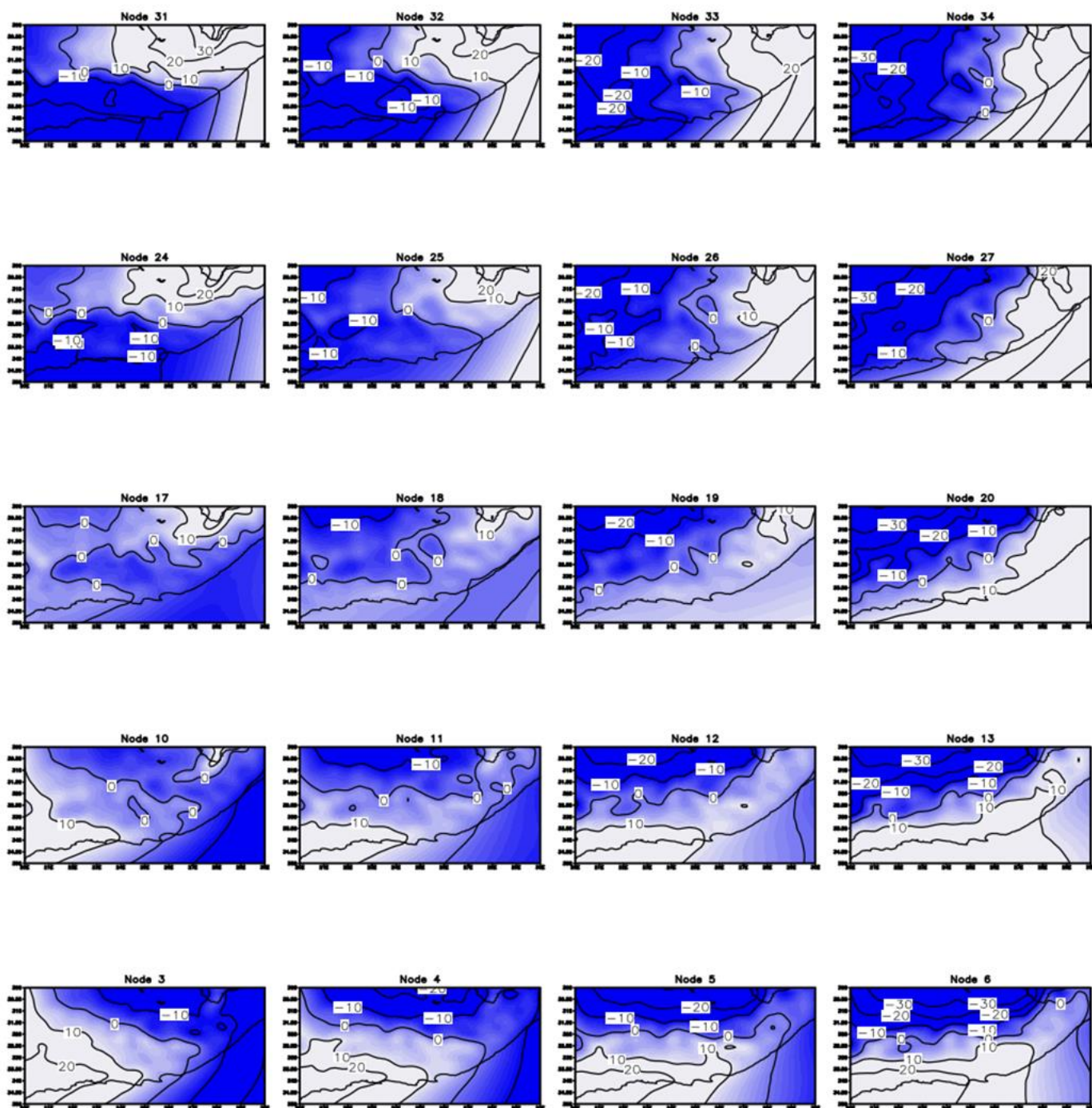
The fields are repeated 4 times for the mean; minimum and std. deviation; in that order.

APPENDIX E: Detailed Trained SOM Results



Legend for geopotential height anomalies in metres



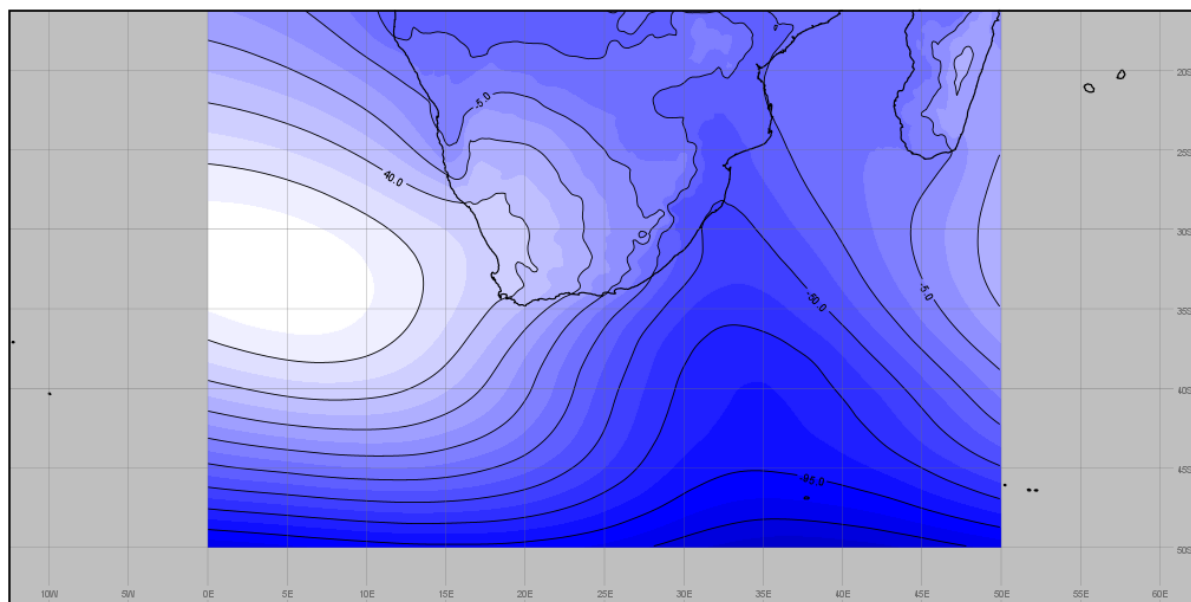


APPENDIX F: Trained SOM Aggregated Synoptic Patterns

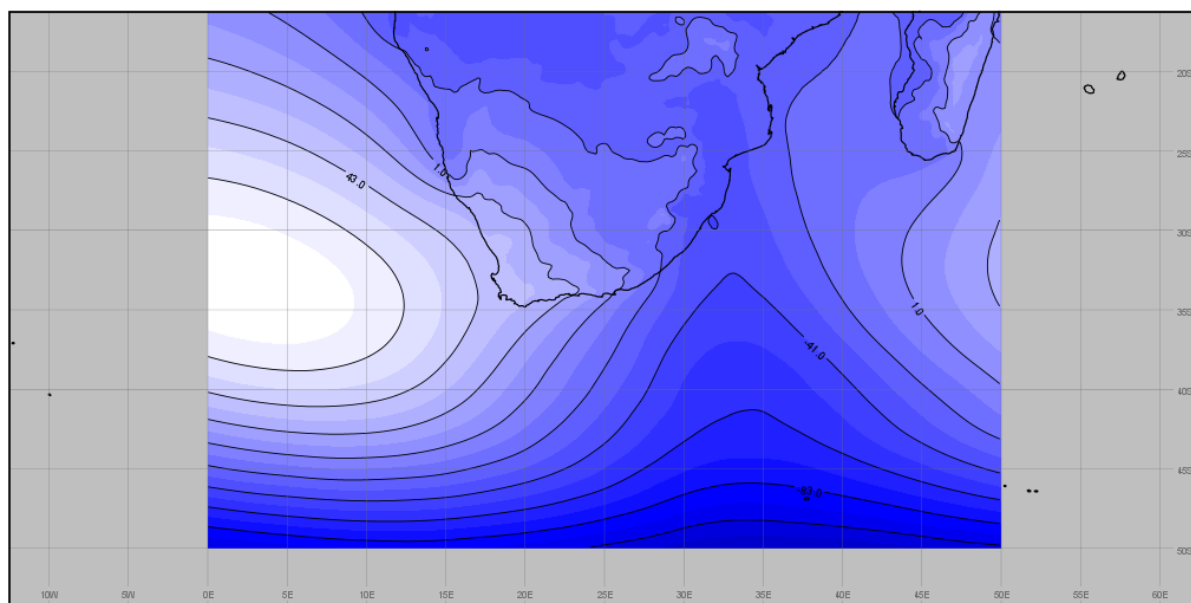


Legend for geopotential height anomalies in metres

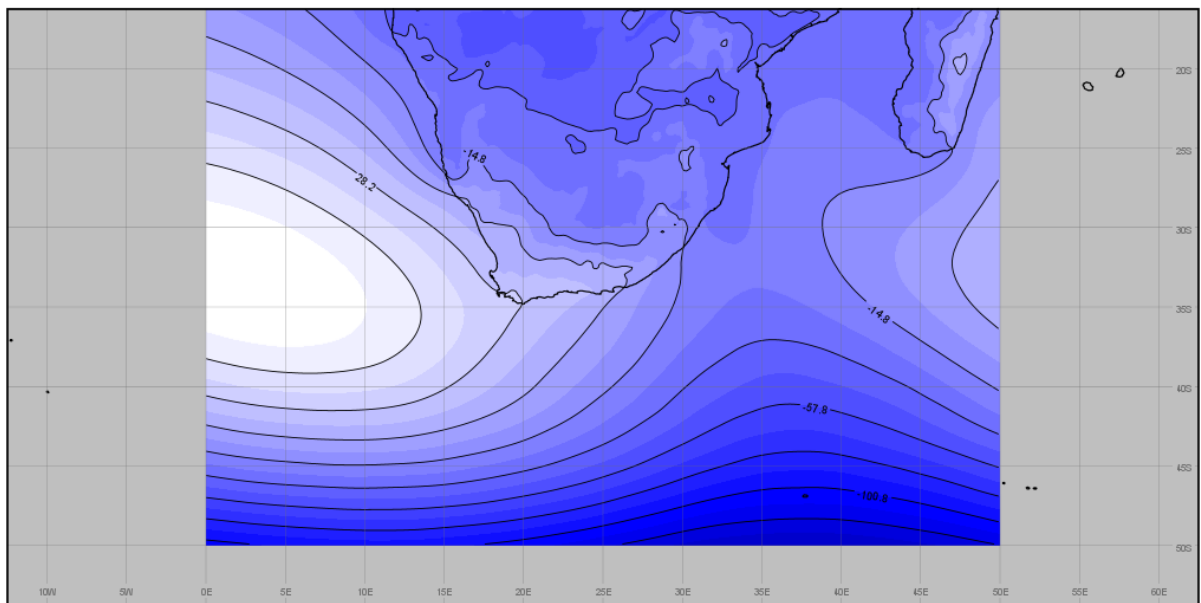
TRAINED SOM NODE 1



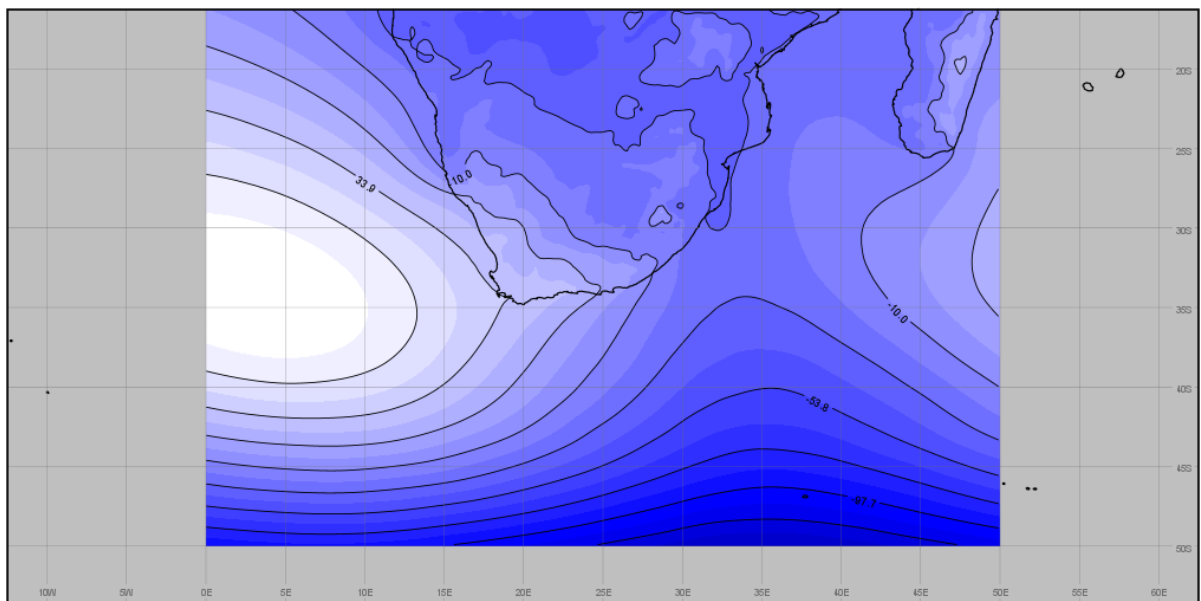
TRAINED SOM NODE 2



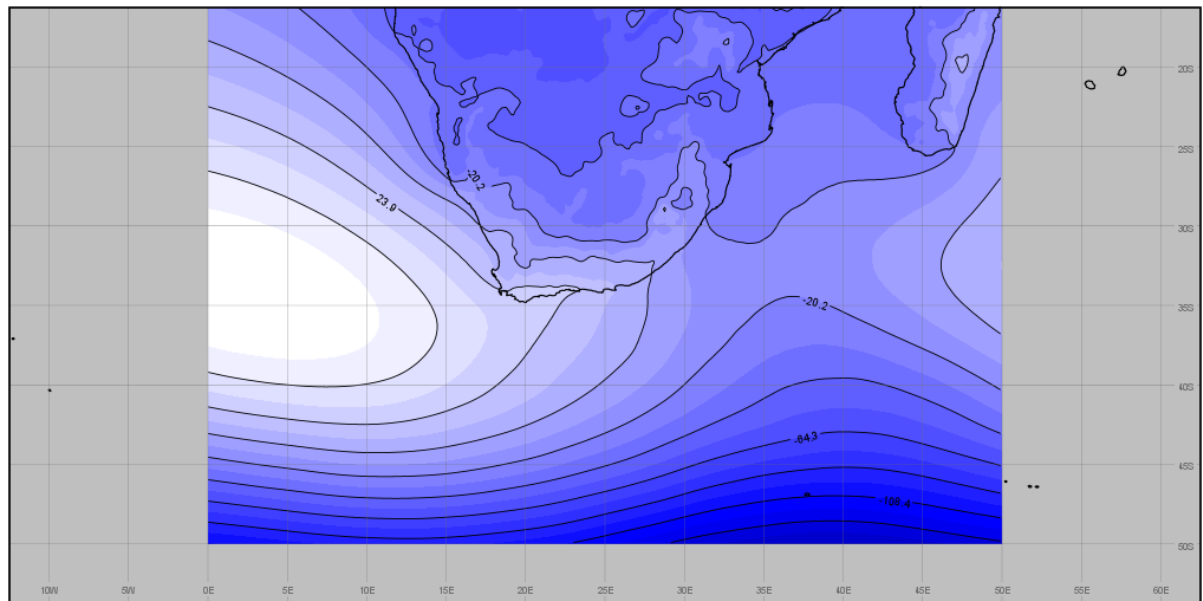
TRAINED SOM NODE 3



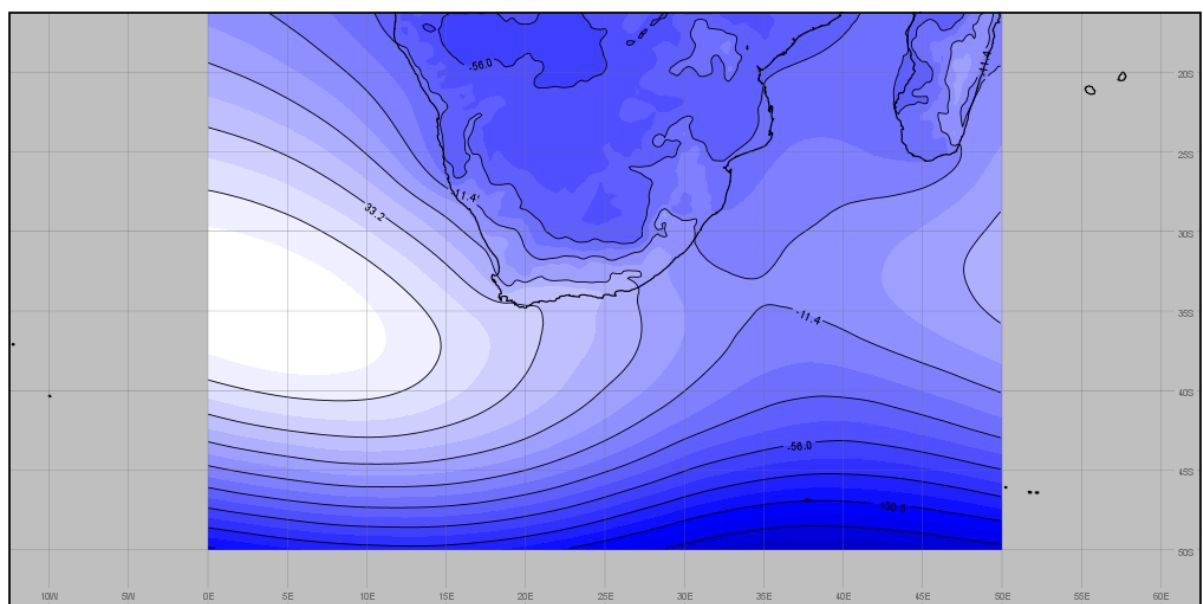
TRAINED SOM NODE 4



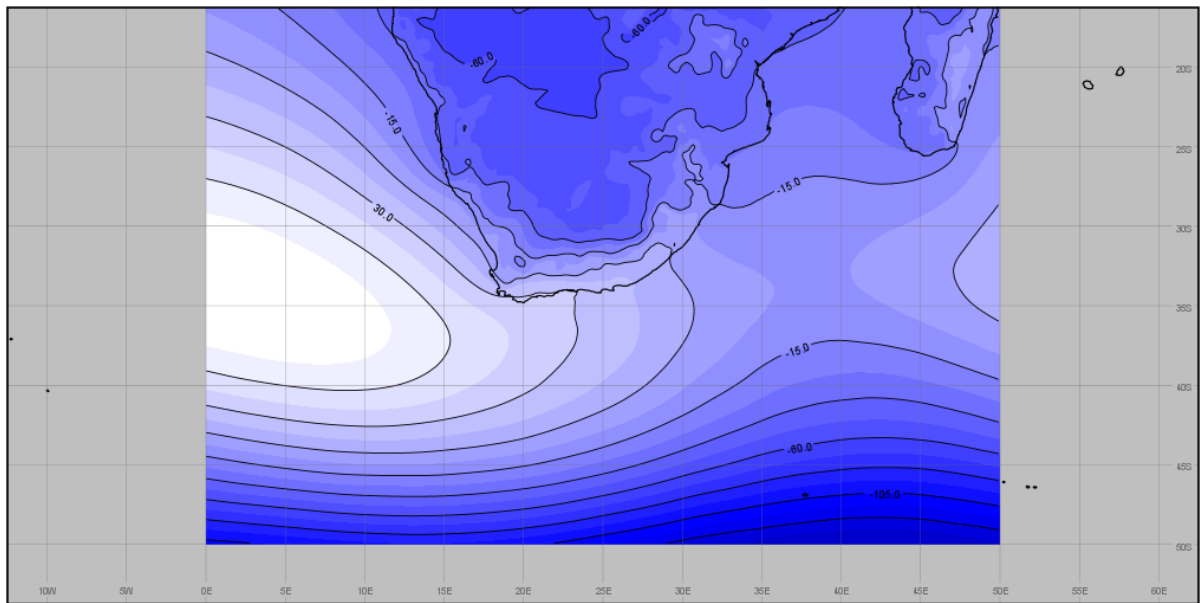
TRAINED SOM NODE 5



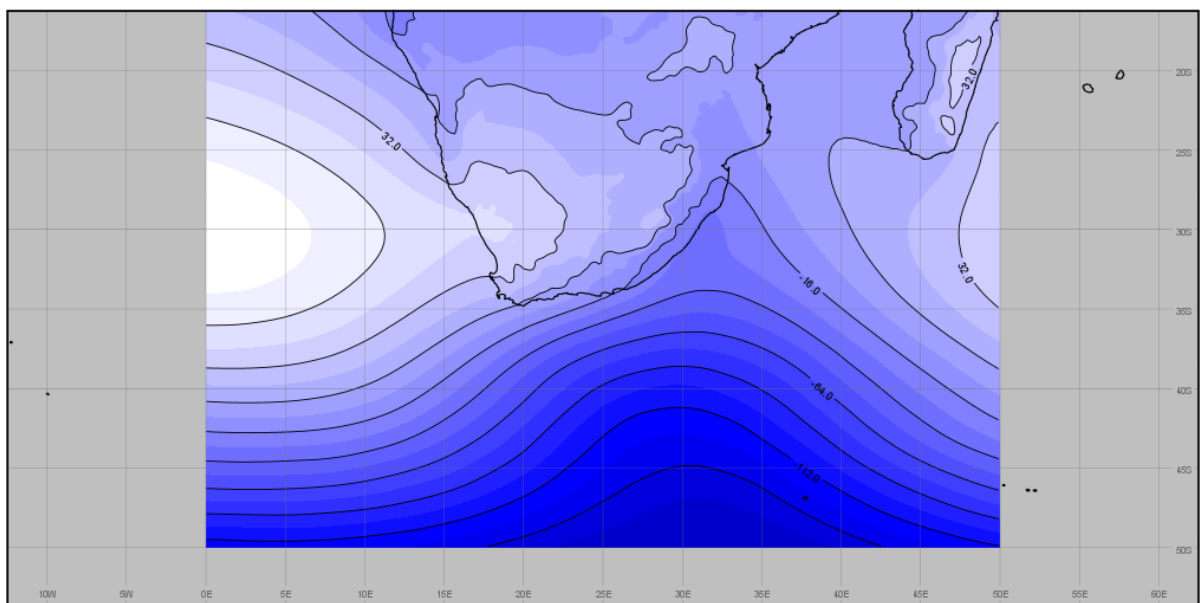
TRAINED SOM NODE 6



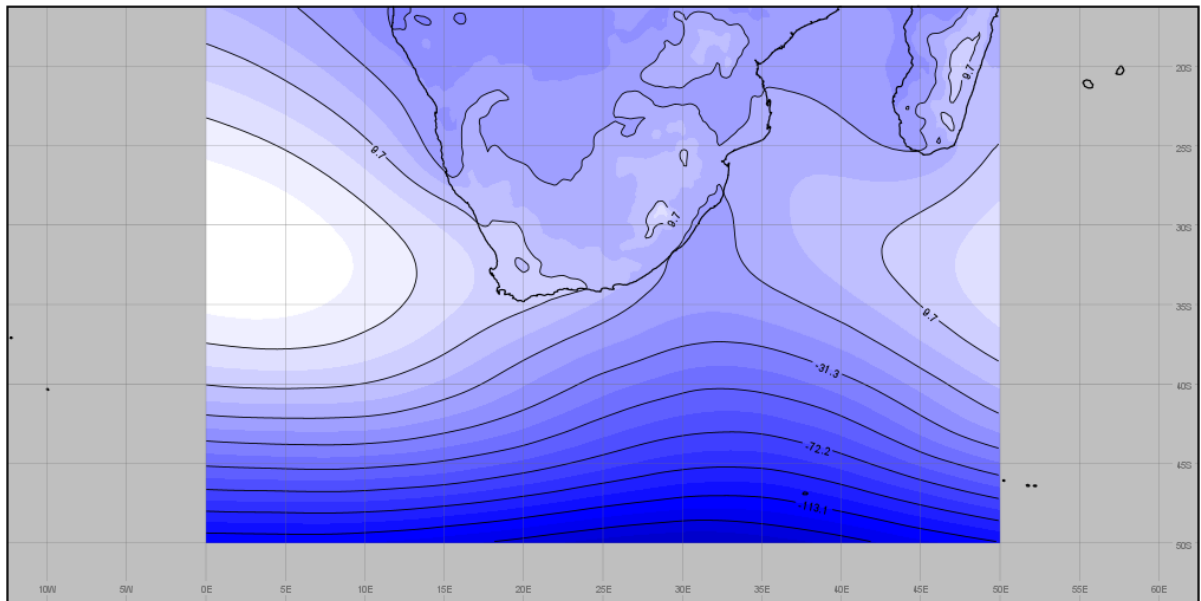
TRAINED SOM NODE 7



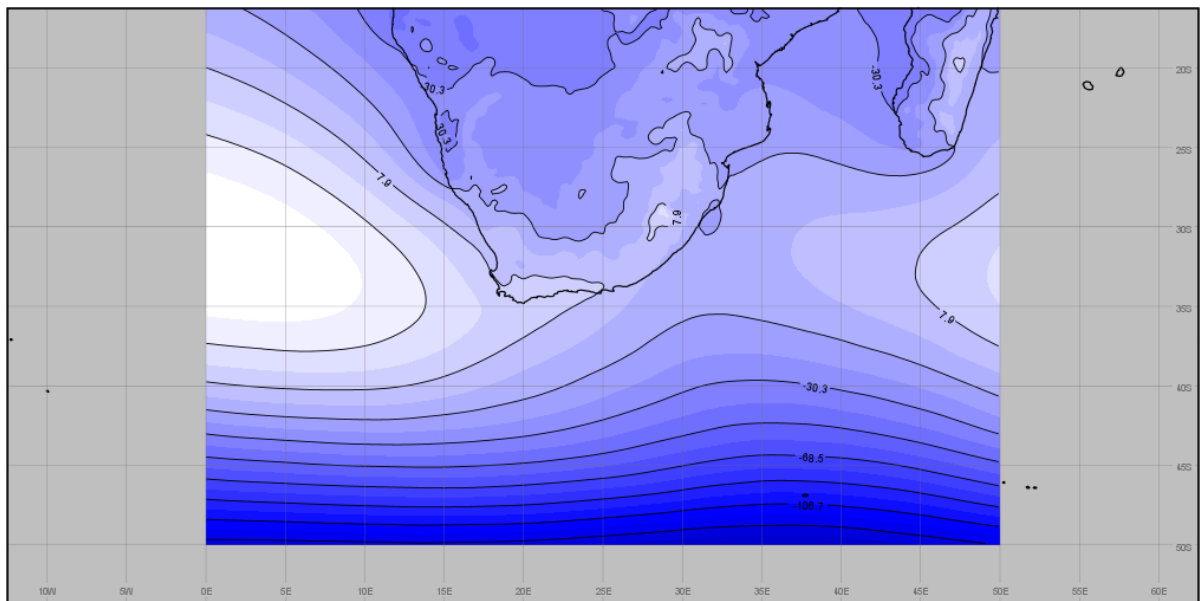
TRAINED SOM NODE 8



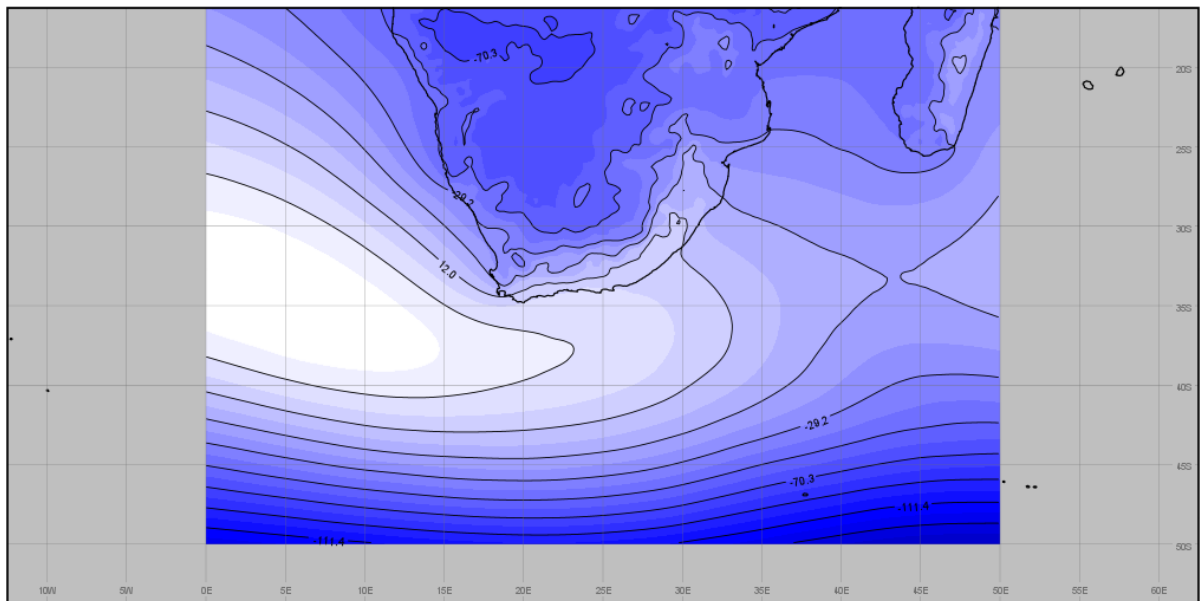
TRAINED SOM NODE 9



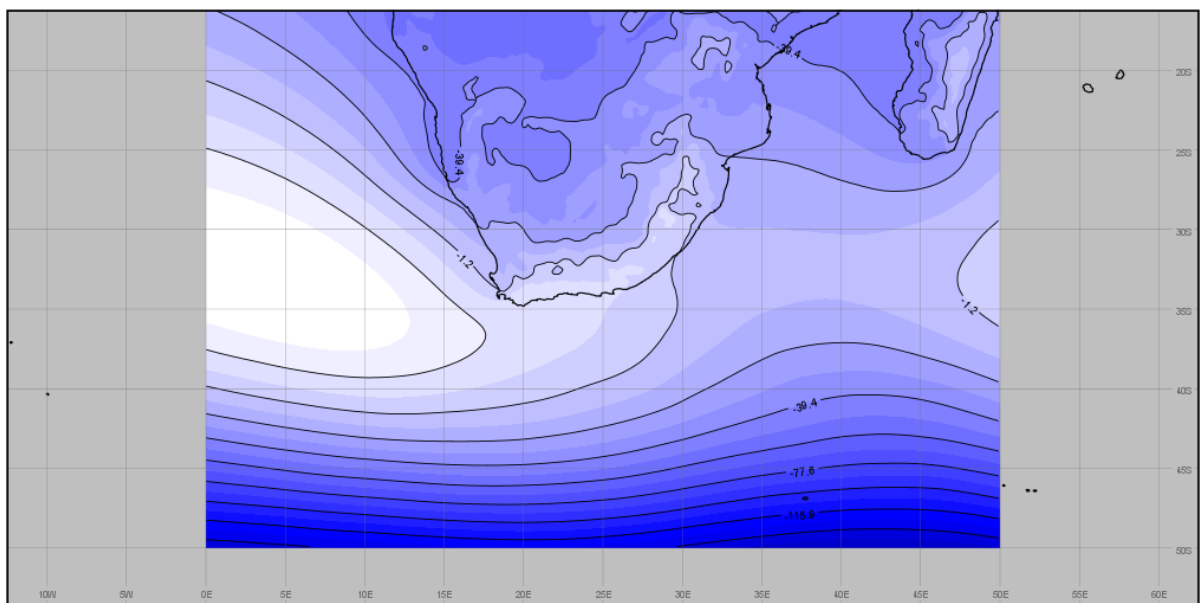
TRAINED SOM NODE 10



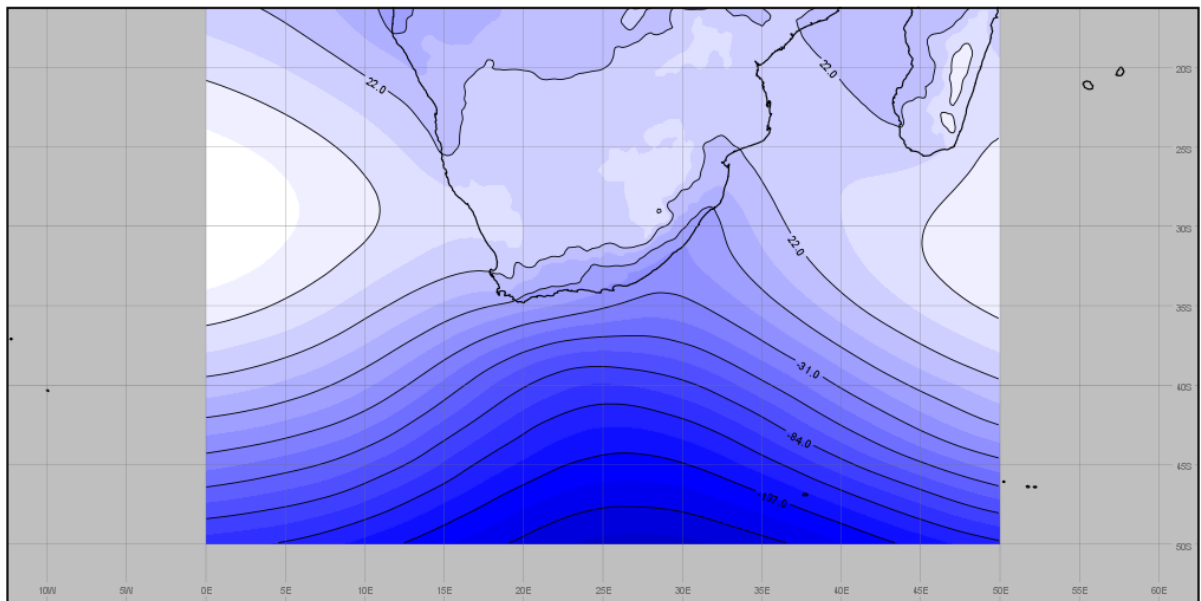
TRAINED SOM NODE 13



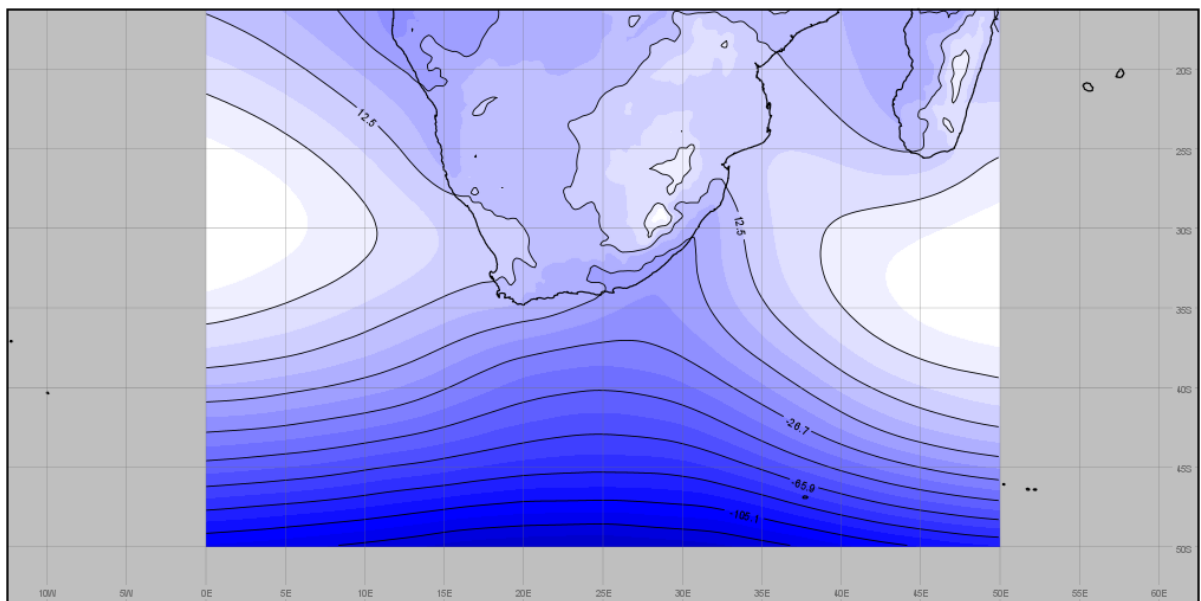
TRAINED SOM NODE 14



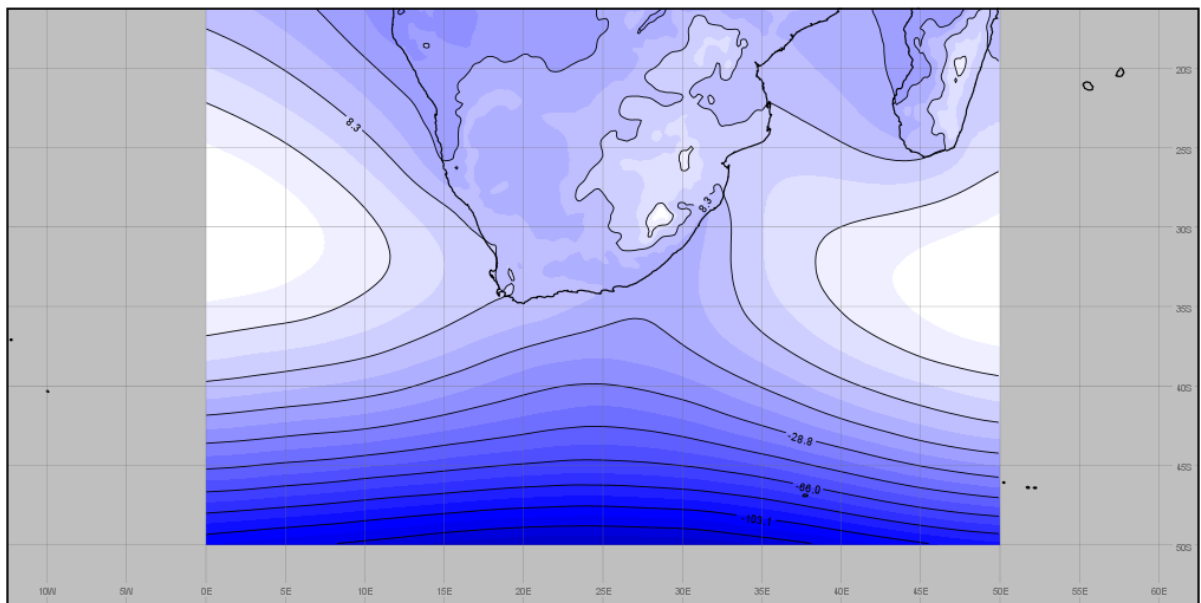
TRAINED SOM NODE 15



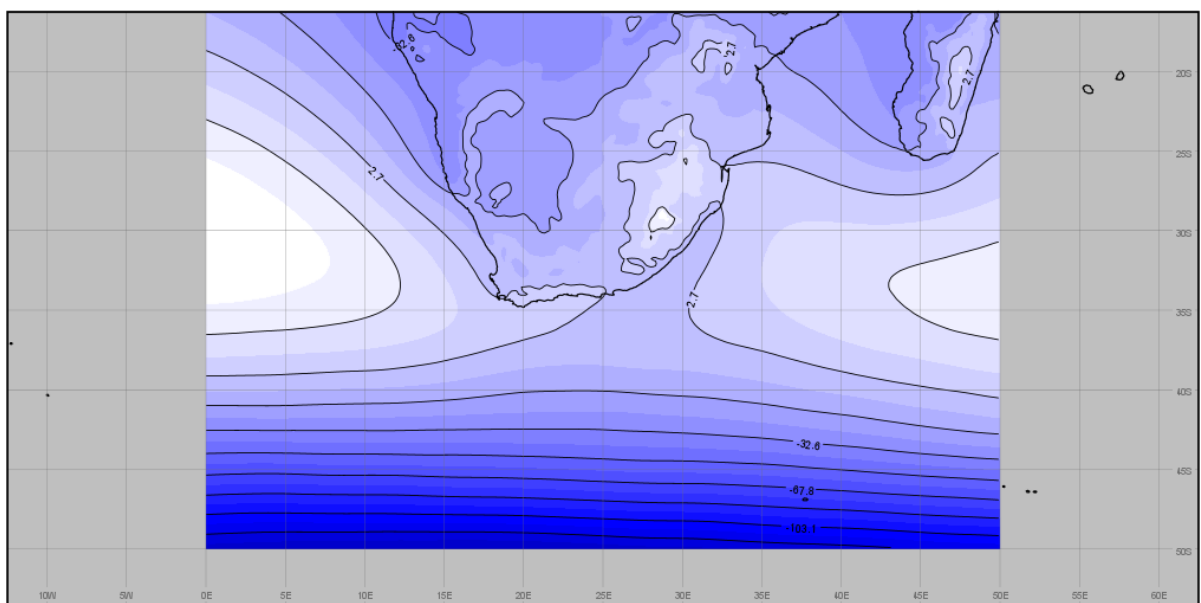
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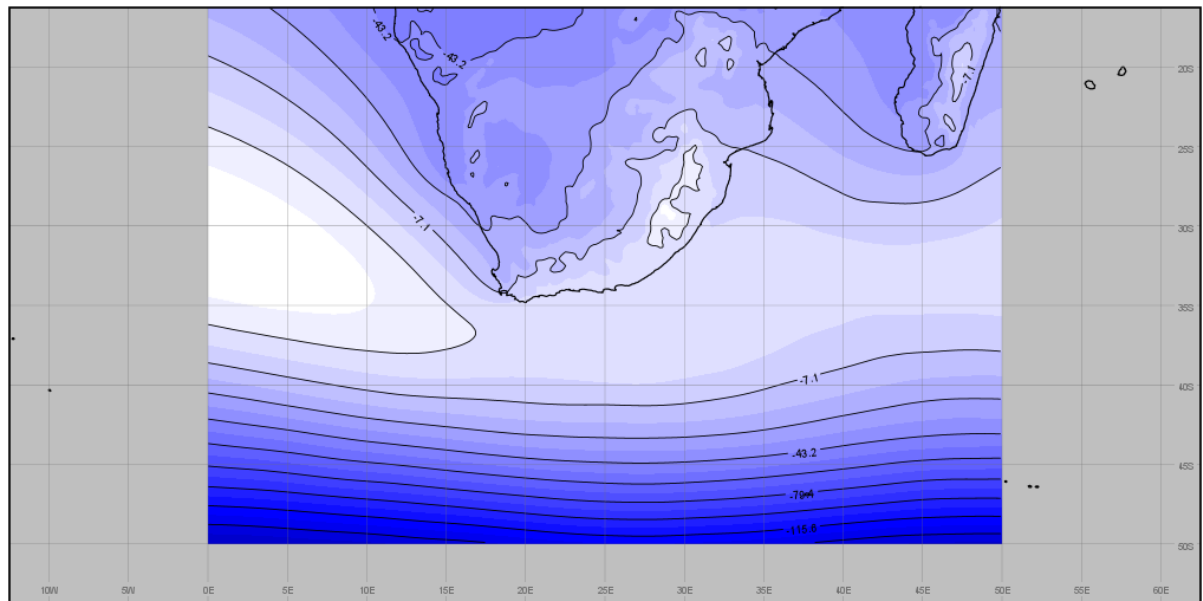
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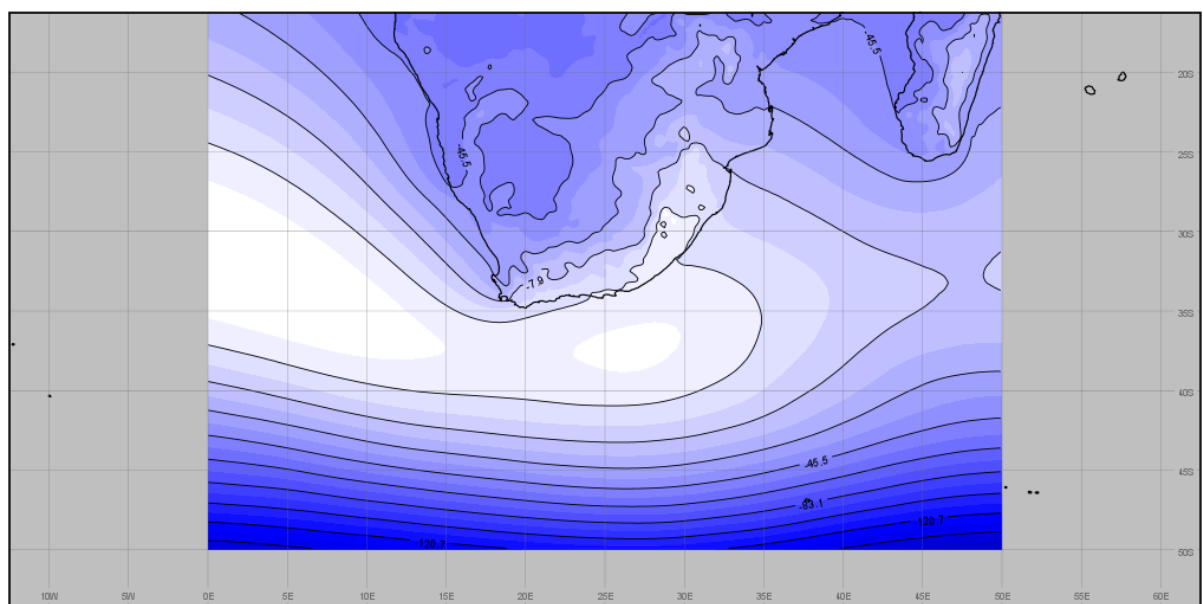
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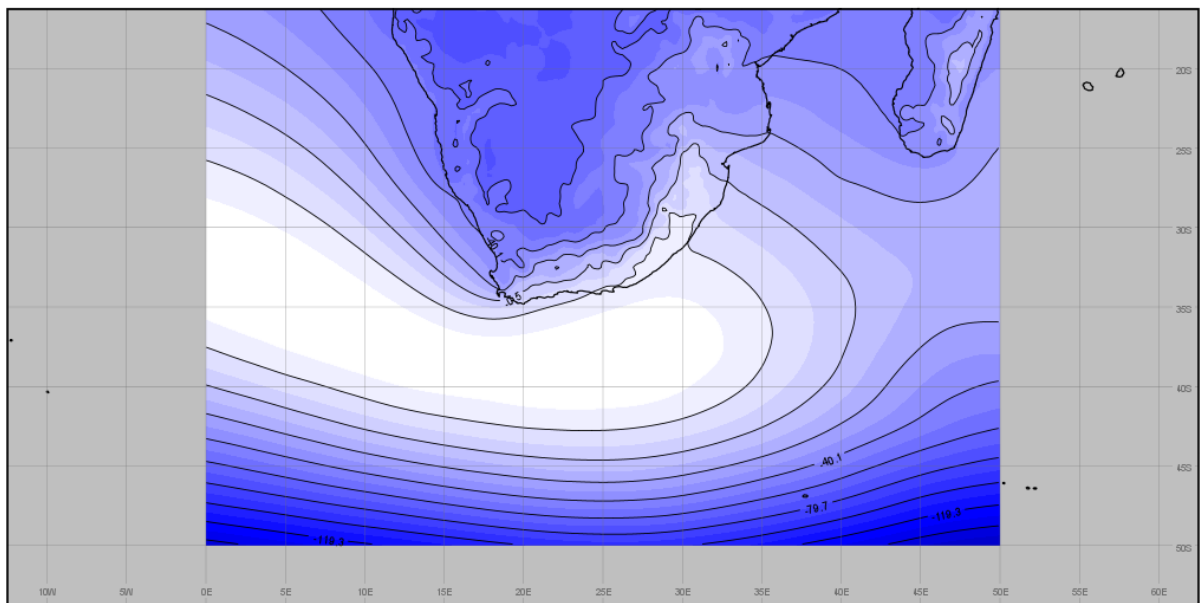
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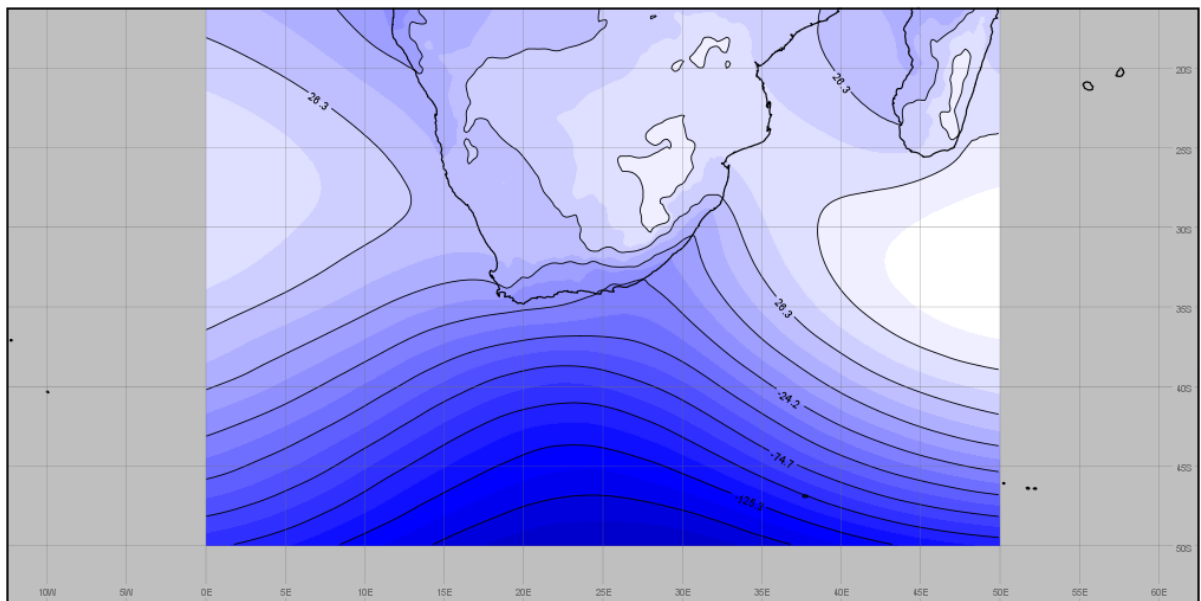
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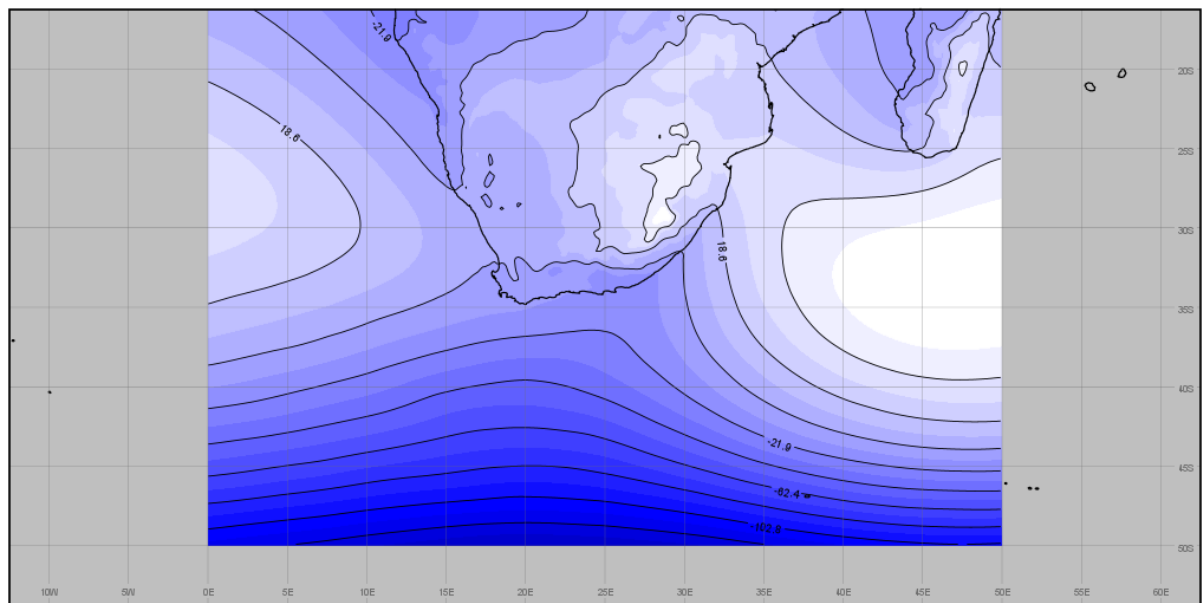
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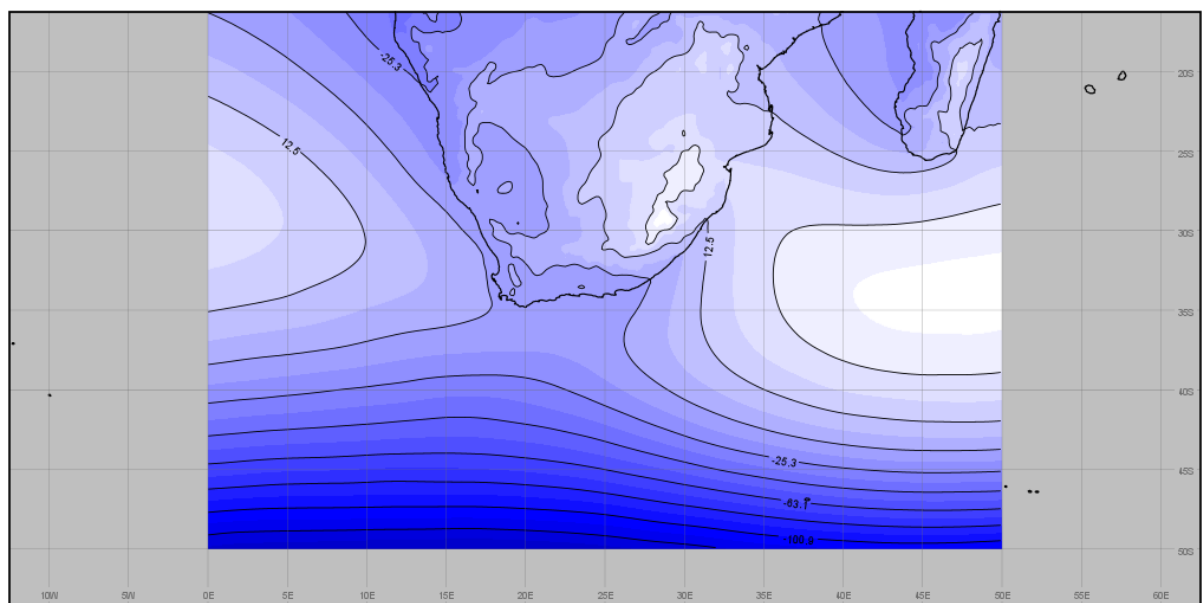
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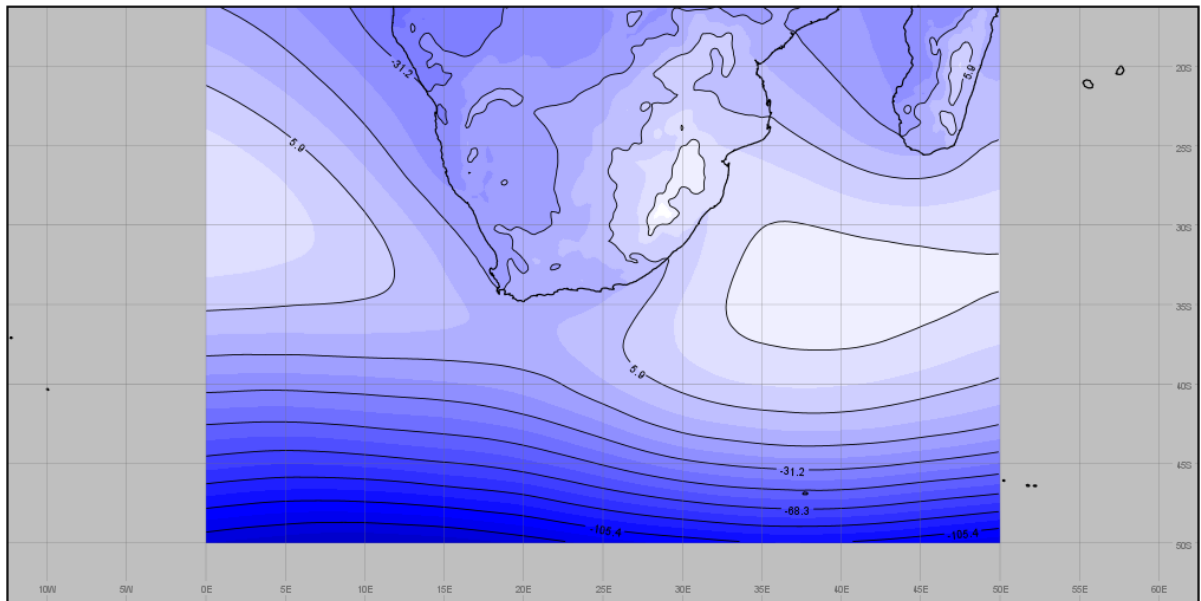
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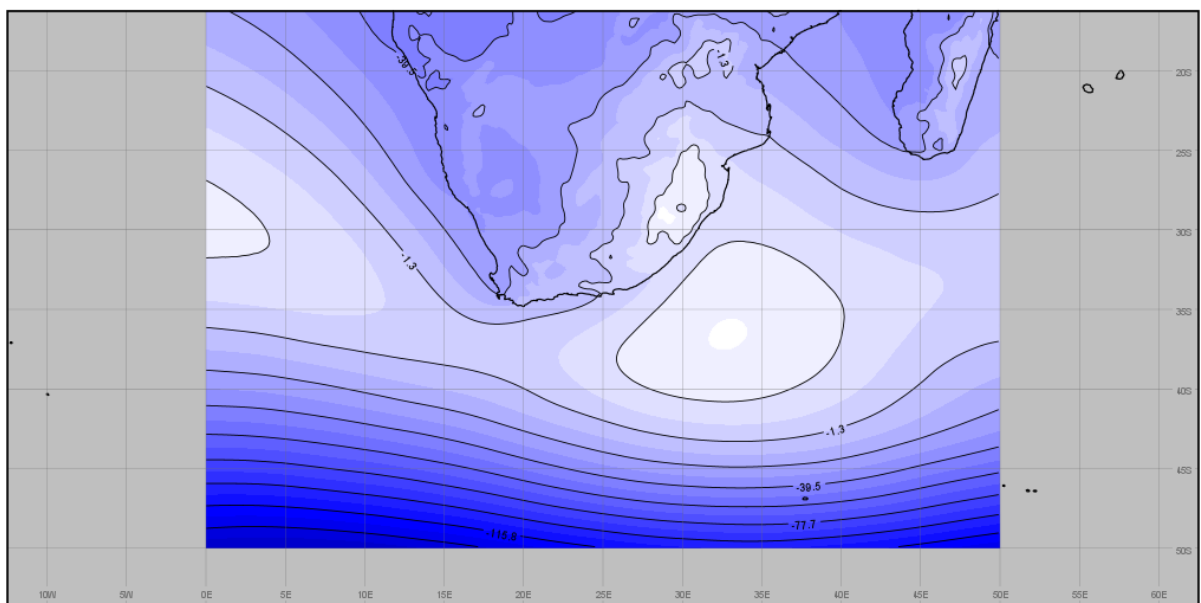
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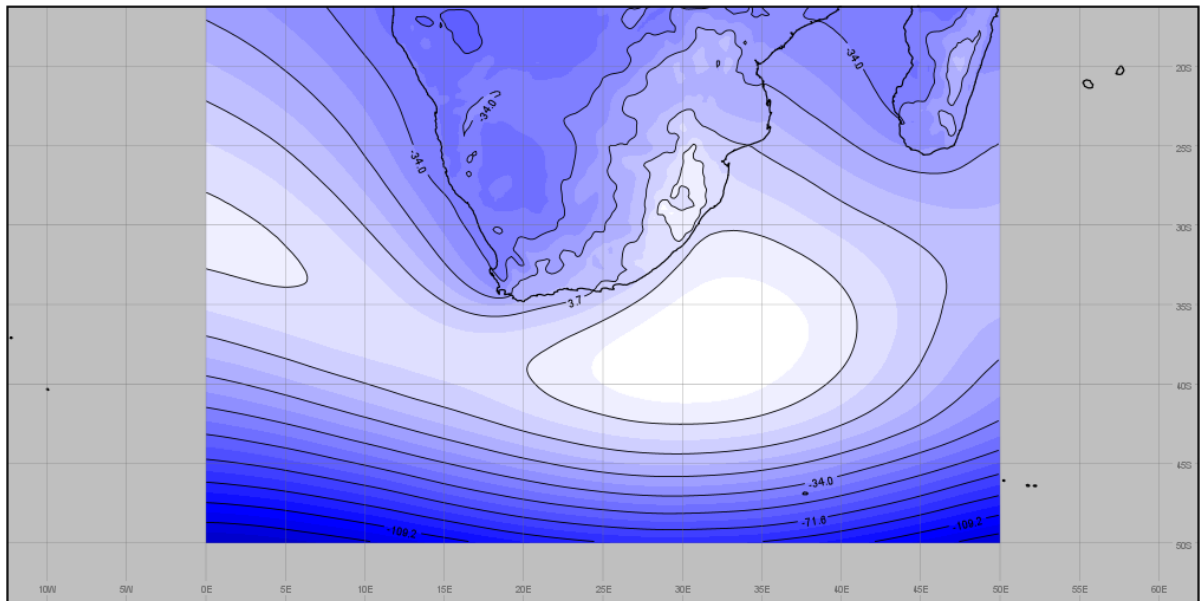
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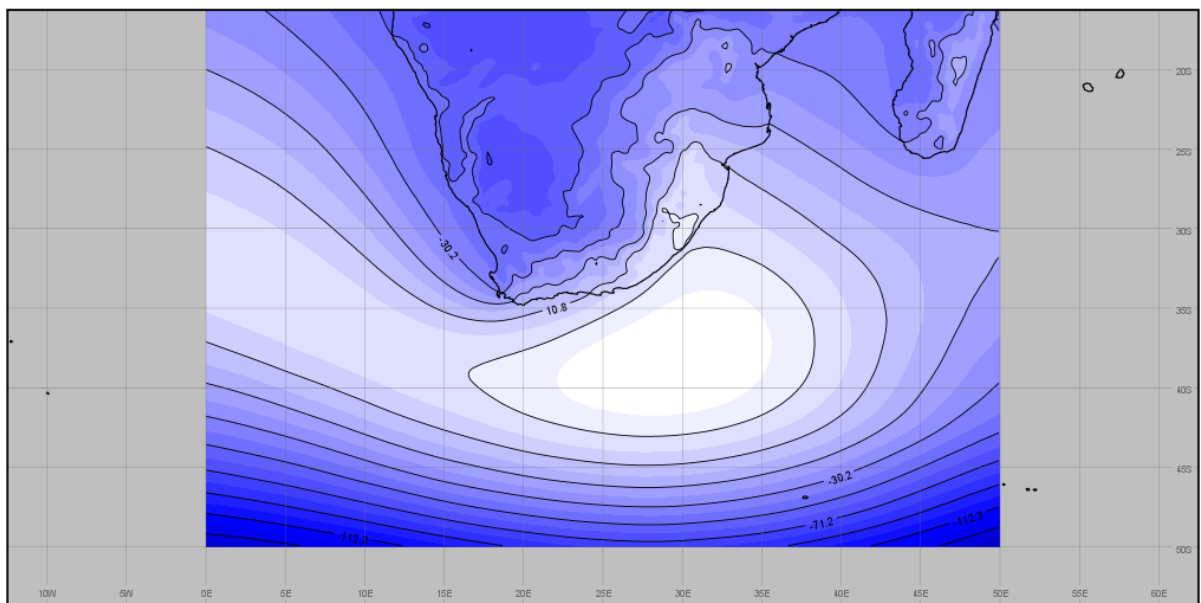
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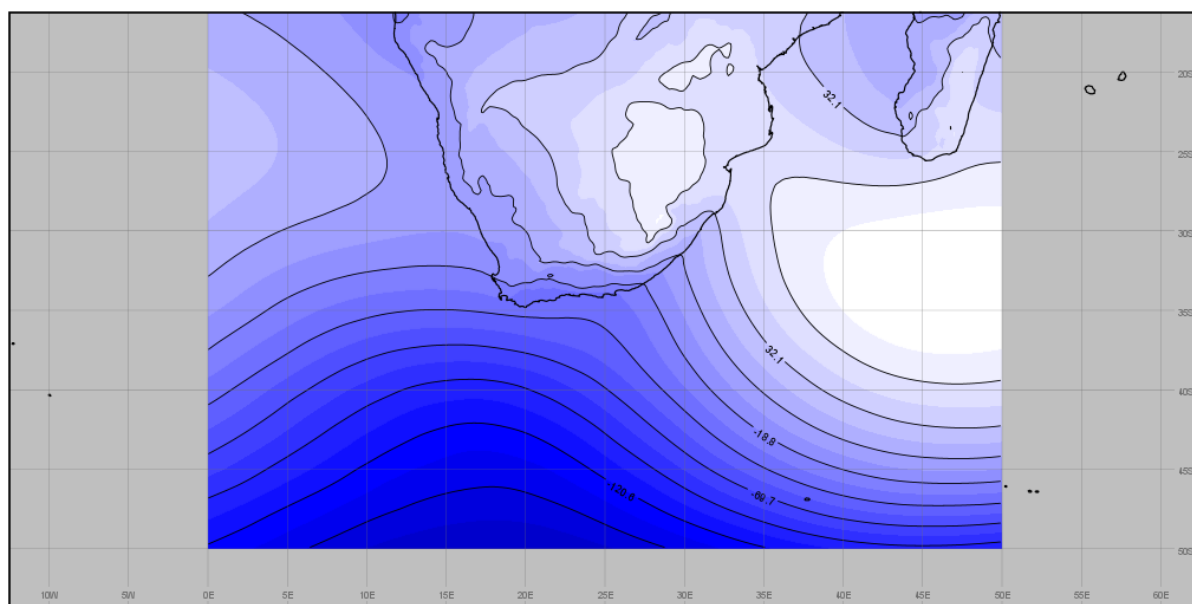
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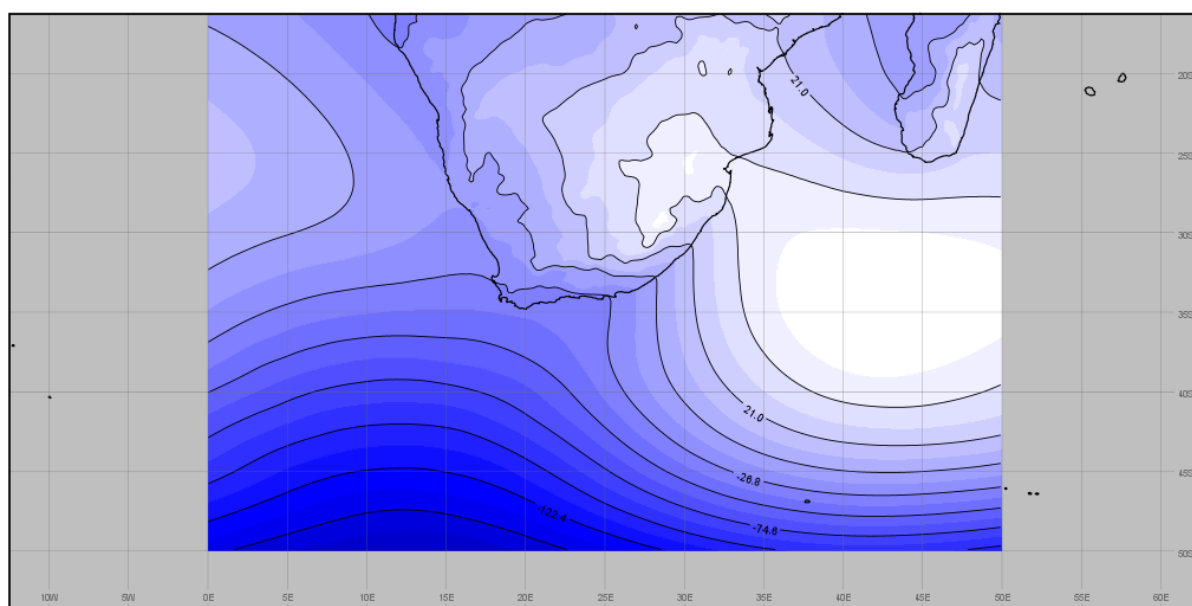
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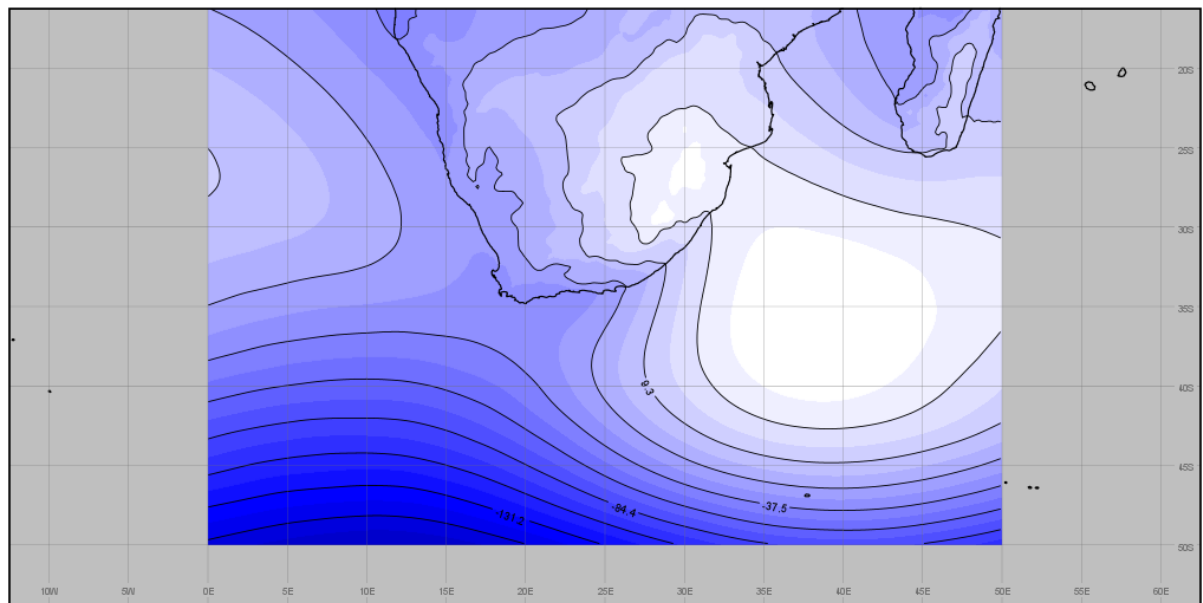
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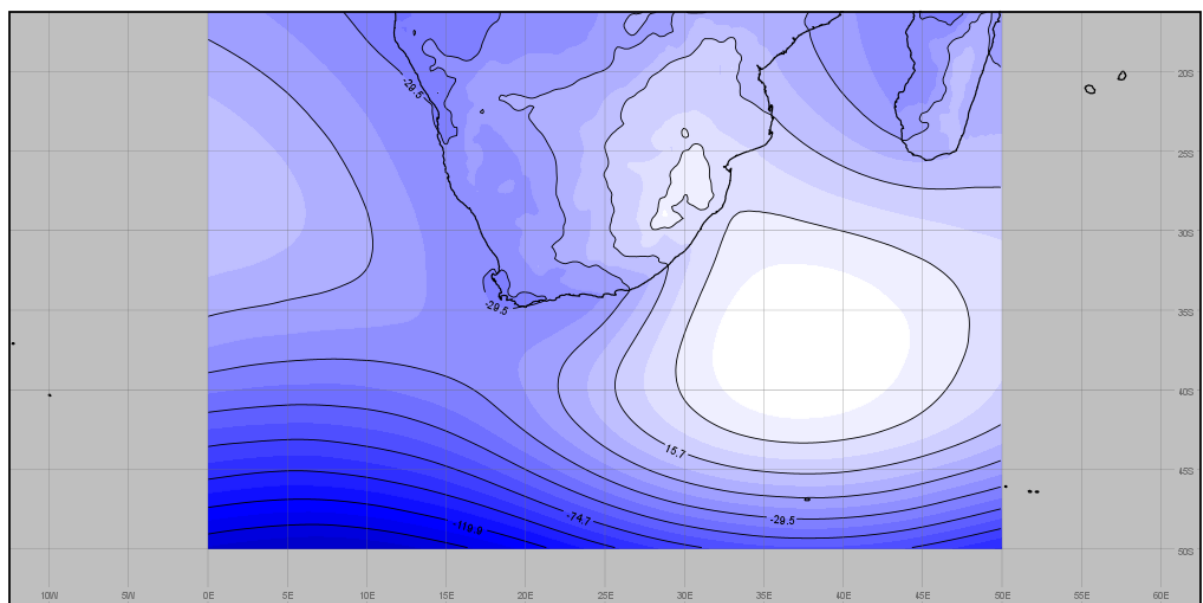
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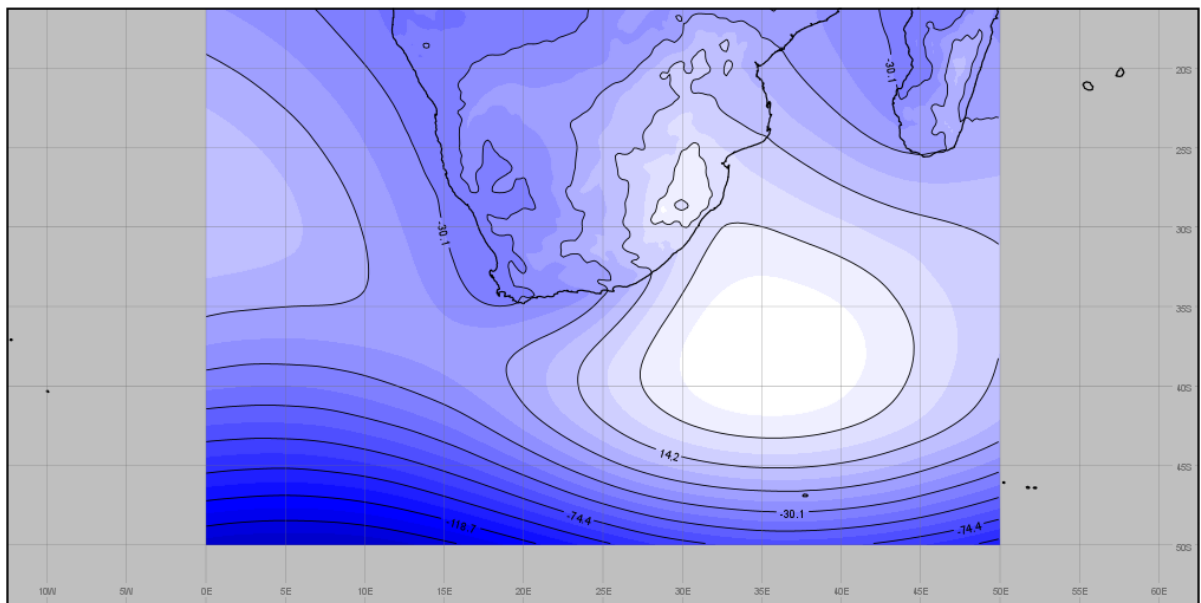
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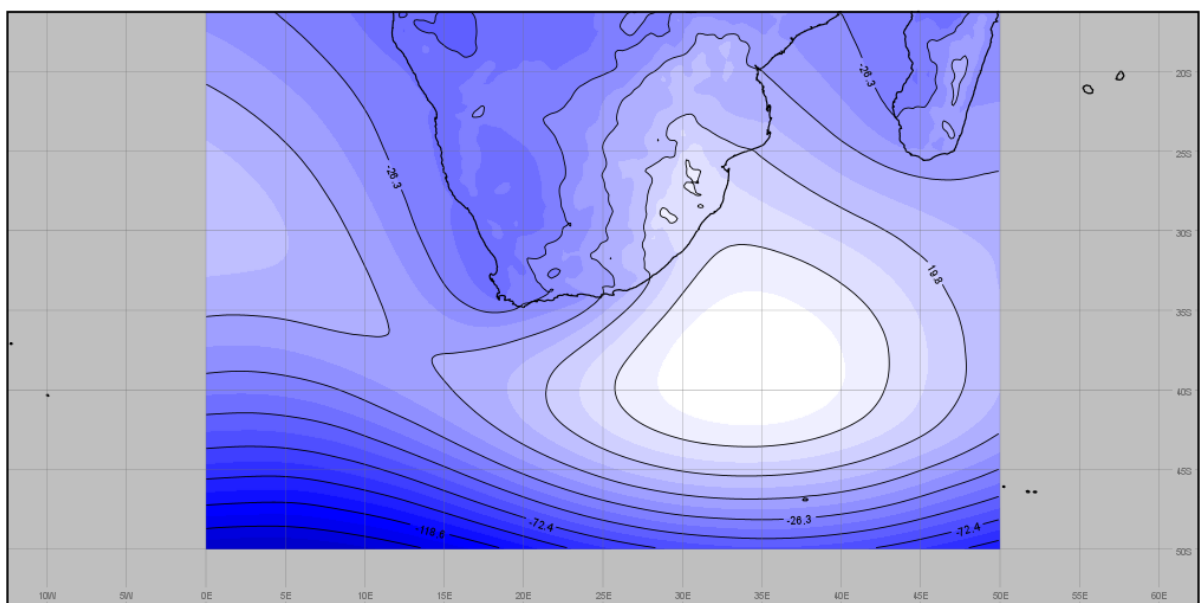
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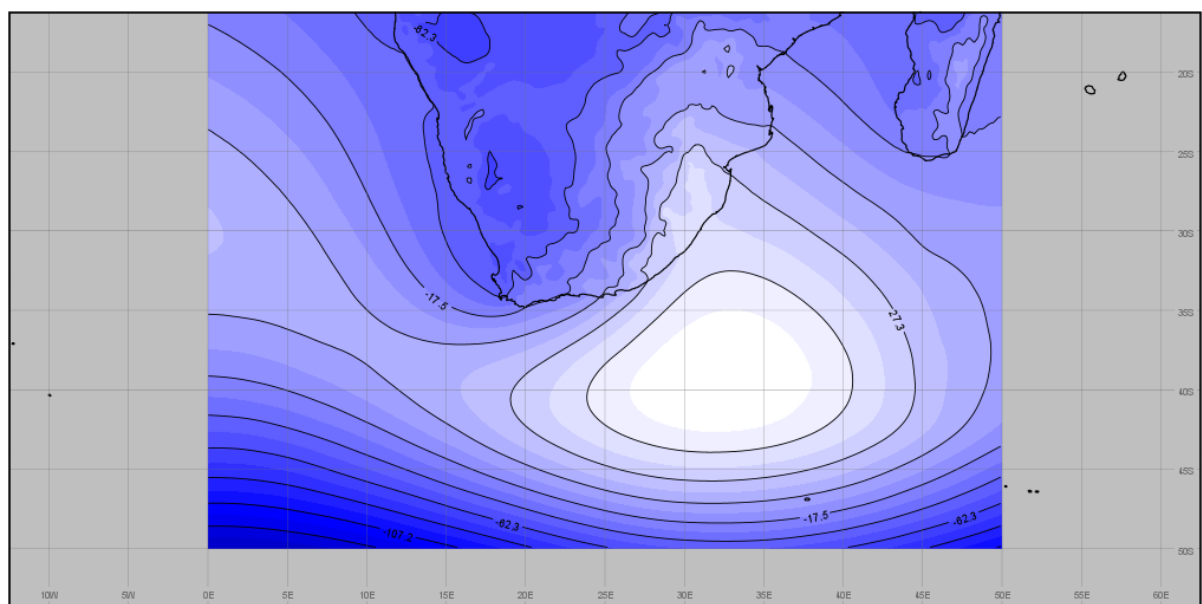
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APPENDIX G: WEF Site Weibull Probability Distribution and Power

Curve

Wind Speed Bin (m/s)	WM07 PDF %	WM08 PDF %	WM09 PDF %	WM10 PDF %	Wind Turbine Generator Power Curve (kW)
0	0.08%	0.45%	0.11%	0.34%	0
0.5	0.42%	0.98%	0.17%	0.75%	0
1	1.16%	1.78%	0.49%	1.73%	0
1.5	2.08%	2.36%	1.00%	2.88%	0
2	2.87%	2.85%	1.63%	3.70%	0
2.5	3.56%	3.33%	2.32%	4.38%	0
3	4.02%	3.88%	2.98%	4.88%	69
3.5	4.42%	4.42%	3.63%	5.30%	155
4	4.77%	4.81%	4.25%	5.53%	263
4.5	5.14%	5.22%	4.81%	5.74%	399
5	5.39%	5.47%	5.23%	5.76%	565
5.5	5.71%	5.45%	5.64%	5.85%	770
6	5.97%	5.45%	5.72%	5.73%	1012
6.5	6.26%	5.44%	5.66%	5.53%	1298
7	6.34%	5.35%	5.58%	5.30%	1630
7.5	6.13%	4.94%	5.41%	5.10%	2014
8	5.80%	4.71%	5.26%	4.70%	2444
8.5	5.29%	4.31%	4.97%	4.34%	2912
9	4.68%	3.88%	4.69%	3.84%	3388
9.5	3.99%	3.53%	4.27%	3.24%	3851
10	3.33%	3.19%	3.74%	2.73%	4287
10.5	2.71%	2.81%	3.37%	2.33%	4683
11	2.16%	2.42%	2.89%	1.91%	5004
11.5	1.73%	2.12%	2.55%	1.56%	5266
12	1.32%	1.83%	2.24%	1.26%	5411
12.5	1.06%	1.58%	1.94%	1.02%	5481
13	0.85%	1.33%	1.64%	0.81%	5500
13.5	0.62%	1.15%	1.43%	0.69%	5500
14	0.49%	0.96%	1.22%	0.57%	5500
14.5	0.40%	0.81%	1.05%	0.45%	5500
15	0.28%	0.65%	0.88%	0.38%	5500
15.5	0.24%	0.55%	0.73%	0.33%	5500
16	0.19%	0.44%	0.59%	0.26%	5500
16.5	0.14%	0.34%	0.46%	0.23%	5500
17	0.11%	0.27%	0.35%	0.18%	5500
17.5	0.08%	0.22%	0.27%	0.14%	5500
18	0.05%	0.17%	0.20%	0.11%	5500

18.5	0.04%	0.13%	0.15%	0.09%	5500
19	0.03%	0.11%	0.12%	0.08%	5500
19.5	0.03%	0.08%	0.09%	0.06%	5500
20	0.02%	0.06%	0.07%	0.04%	5500
20.5	0.01%	0.05%	0.05%	0.04%	5500
21	0.01%	0.03%	0.04%	0.03%	5447
21.5	0.00%	0.02%	0.03%	0.02%	5382
22	0.00%	0.02%	0.02%	0.02%	5240
22.5	0.00%	0.02%	0.02%	0.01%	5050
23	0.00%	0.01%	0.01%	0.01%	4841
23.5	0.00%	0.01%	0.01%	0.01%	4679
24	0.00%	0.01%	0.01%	0.01%	4549
24.5	0.00%	0.00%	0.00	0.00%	4457
25	0.00%	0.00%	0.00	0.00%	4387

APPENDIX H: Published version of Paper 1 (Chapter 6)



Wind energy potential of weather systems affecting South Africa's Eastern Cape Province

Greg Landwehr¹ · Chris Lennard² · Francois Engelbrecht¹

Received: 1 June 2023 / Accepted: 2 January 2024 / Published online: 27 January 2024
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Abstract

As a percentage of the total global energy supply, wind energy facilities could provide 10% of the total global energy supply by 2050 as reported in IEA World Energy Outlook (2022). Considering this, a just transition to renewable and sustainable energy in South Africa is a genuine possibility if steps are taken immediately to achieve this. The Eastern Cape Province exhibits a strong wind resource which can be exploited towards expediting such a just energy transition. No research and related modelling have, to date, been undertaken in quantifying and relating the detailed P50 energy yield analyses of representative wind energy facilities in temporal and spatial dimensions to the occurrence of specific synoptic types in South Africa. To quantify this energy meteorology climatology for a suitably sized geospatial area in the Eastern Cape Province of South Africa (spatial focus area, latitude -30 to -35 , longitude 20 to 30), the approach of using self-organising maps is proposed. These maps are used to identify the most common synoptic circulation types occurring in the Eastern Cape and can subsequently be mapped onto an equivalent time resolution wind energy production timeseries calculated based on probable wind energy facility sites. This paper describes comprehensive methodologies used to model the wind energy facilities, calculate with high confidence the P50 energy production, and then identify the predominant synoptic weather types responsible for the wind energy production in this spatial focus area. After quantifying the energy production, running a self-organising map software generates a purposely selected 35 node map that characterises archetypal synoptic patterns over the 10-year period. The synoptic types can be ranked by the highest energy production. It is shown that in this spatial area, monthly wind energy production is higher during the winter months. When the well-established high-pressure cells move northward, synoptic types associated with higher energy production are frequent and include tropical and temperate disturbances across South Africa, patterns resembling a ridging anticyclone off the west coast of South Africa and low-pressure cells occurring to the north and south. Low energy producing patterns show characteristics of the high-pressure cells moving southwards producing fine weather and mildly disturbed conditions. The purpose of this methodology is that it provides the foundation required to derive long-term frequency changes of these synoptic weather systems using global climate model ensembles and thus changes in wind energy production.

1 Introduction

In South Africa, a seminal paper on renewable energy, written in 2003, recognised that the long-term potential of renewable energy is substantial (Department of Mineral Resources and Energy 2003). Wind energy has also been given priority by the Integrated Resource Plan (IRP) (Department of Mineral Resources and Energy 2019). This positive outlook for renewable energy, in particular wind energy, in South Africa requires long-term strategic planning to realise that potential.

A single wind energy facility (WEF) typically takes 2 to 4 years to build (Department of Mineral Resources and Energy 2022) and integrating such facilities with existing distribution

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and transmission networks requires consultation with utilities on tie in solutions whilst always referencing their Generation Connection Capacity Assessment (GCCA) (Eskom Holdings 2022). WEF development is dependent on the strength of the wind resource itself and the process involved requires onsite measurement instruments as well as well-defined statistical techniques to characterise the wind resource. As a rule, banks and other investors demand at least 1 year of measured wind resource data and an independent third-party evaluation from a well-established energy yield consultant before committing investment to a new WEF.

As part of deciding the location of a new WEF, climate variability and change should be considered. Important is optimal energy production over the lifespan of the generators and associated power purchase agreement (PPA), which may well be 20 years or longer. Such planning extends to the reuse of the site after the wind turbine generator (WTG) lifespans are over implying, the need to include climate change assessments beyond the near-term (the next 20 years).

In this study, the Eastern Cape (EC) of South Africa is selected as the area of interest since it has strong potential for WEF development with annual average wind speeds of greater than 7.2 m/s (at 62 m, the local Wind Atlas of South Africa (WASA) mast's highest anemometer) and capacity factors above 40% at the sites investigated in this paper. The province has and is expected to be extremely competitive in the future bid rounds of the Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) and private sector PPAs (Department of Mineral Resources and Energy n.d.).

To characterise the wind potential of the Eastern Cape in more detail, four fictitious WEFs are modelled, each purposefully located close to the WASA (The wind atlas of South Africa n.d.) meteorological masts. These masts provide 10 years of 10-min average wind resource measurements, from 2010 to 2019. This allows for the energy production at P50¹ level to be calculated with high certainty given the 10-year measurement period.

To quantify the energy-meteorology climatology of the Eastern Cape Province of South Africa, a synoptic typing methodology is used to objectively identify the main synoptic weather systems that provide wind potential to the province. Characterising these synoptic types and the resultant energy production associated with each can inform WEF siting for both the current climate and future climate that may change due to global warming.

This paper begins by presenting the background information in Section 2 which is necessary to generate the results. Methodologies used in the study are presented in detail in Section 3 and the results and discussion follow in Section 4, with conclusions drawn in Section 5.

2 Background

2.1 South African electricity supply system

South Africa exhibits one of the most carbon-intensive electricity supply systems in the world and is currently striving towards a 'Just Energy Transition' which is less carbon-intensive (European Commission 2022). South Africa's power Generation, Transmission and Distribution systems are dominated by Eskom.² The parastatal generates 90% of South Africa's electricity with a current power plant capacity for South African consumption of approximately 46.5 Gigawatts (GW) most of which comes from coal (Eskom Holdings n.d.). This varies at any one time due to electricity trading with neighbouring countries and issues such as load shedding and unforeseen plant maintenance. As per the latest South African census, the electrification ratio in South Africa is at 87% (South African census 2011).

During the last decade, South Africa has developed approximately 6 GW of combined wind, solar photovoltaic (PV), and concentrated solar power (CSP) (CSIR Energy Centre Analysis 2020). Projections made by the Department of Mineral Resources and Energy show that the electricity generation capacity of South Africa could rise to 109 GW by 2050 with 33% (capacity and electricity production) coming from wind alone (Department of Mineral Resources and Energy 2019). If such a change materialises, it will have extensive benefits beyond energy generation and would contribute to South Africa's emissions reduction efforts.

2.2 WEF siting

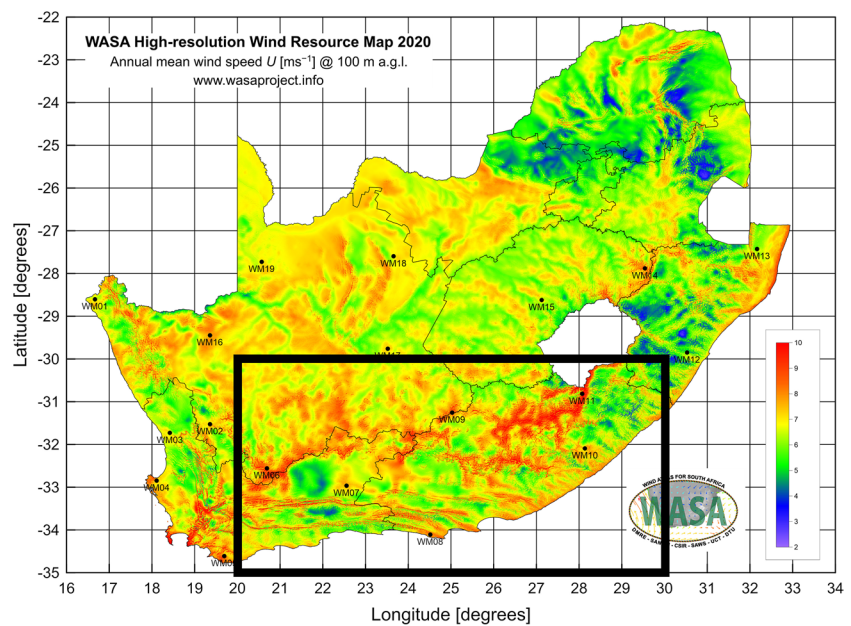
Of course, WEF siting can follow different methodologies; however, the following description provides a general overview of the major steps that any WEF siting exercise will employ. Initially, mesoscale average annual wind speed and power density³ maps are used to select pre-feasibility positions for WEFs. Once a pre-feasibility position is selected, it is scrutinised against a set of pre-feasibility criteria such as proximity to the electrical grid, avifaunal/faunal no-go

¹ P50 energy yield: the net annual energy production (AEP) value is considered the 'P50' energy yield value and constitutes the gross AEP value less losses that has the probability of being exceeded by 50% of all AEP's that could be possible for the site involving the uncertainties associated with the estimate.

² Eskom: Eskom Holding SOC. Ltd. is South Africa's primary electricity supply utility.

³ Power density: mean annual power available per square metre of rotor blade swept area of a suitable WTG.

Fig. 1 The geographic location of the study region within South Africa using the WASA wind speed map (colour bar shows annual average wind speed in m/s) (The wind atlas of South Africa n.d.)



areas, protected flora areas, proximity to existing buildings and infrastructure, and road access.

Once the site passes this screening, feasible wind turbine layouts are created based on wind flow maps which are created using the onsite measurement data. The WEF layout design is undertaken using specialised WEF modelling software (sometimes requiring computational fluid dynamic analysis for complex terrain) which considers terrain, roughness, and wake losses. Then, high level net capacity factor (NCF⁴) and AEP⁵ calculations are completed to verify the attractiveness of the site. These calculations are based on at least 1 year of observed measurements from the site.

2.3 Geospatial area of interest

The Eastern Cape Province of South Africa (Fig. 1) has a strong potential for wind energy. The WASA map (The wind atlas of South Africa n.d.) shows a significant part of the Eastern Cape Province having annual average wind speeds in the order of 7–8 m/s and accompanied by wind power densities in the order of 300–600 W/m². This makes the Eastern Cape a viable location for utility scale wind farms. As a reference dataset for selection of the spatial area of interest, WASA is an important reference. Similar Wind Atlases

have been developed to provide comparable insights globally (Hahmann et al. 2020; Nassar et al. 2023).

Accompanying these high annual average wind speeds are very attractive NCFs which can range between 35 and 45% for the Eastern Cape and have been extremely competitive in the past bid rounds of the REIPPPP (Department of Mineral Resources and Energy n.d.). In contrast to this, similar quality sites (Global Wind Atlas, 2023) with high density of WEFs installed exist in North Brazil (~45% NCF), the Egyptian coast of the Gulf of Suez (~50% NCF), Northern Germany (~40%), and South India (~40%).

Four fictitious WEF sites (Fig. 2) have been selected to adequately cover the selected area of interest and have been chosen due to their proximity to four WASA masts. Furthermore, they are named after the WASA masts from which the energy production timeseries is derived, WM07 (−32.967°, 22.556°), WM08 (−34.110°, 24.514°), WM09 (−31.252°, 25.031°), and WM10 (−32.092°, 28.136°) and are located between 5 and 10 km from their namesake WASA mast to the outermost WTGs. Energy production at P50 level can thus be calculated with high confidence since it is based on 10 years of high-resolution wind resource measurements from 2010 to 2019 taken from the WASA.

The general WEF and WTG specifications used for the modelling are provided in (Table 1):

2.4 Synoptic-scale weather systems impacting on the Eastern Cape

Located in Southern Africa, south of 30°S, the climatology of the Eastern Cape is determined by a range of different weather systems that originate in climatological circulation

⁴ Net capacity factor: the actual annual net energy yield / theoretically possible annual energy yield if the plant ran at full capacity all year around. $NCF = \text{Actual Energy Generated less all losses (MWh)} / (\text{Plant Capacity (MW)} \times \text{Time Period (h)})$

⁵ Annual energy production: actual annual gross energy production less losses

Fig. 2 WEF geographical positions within the geospatial focus area

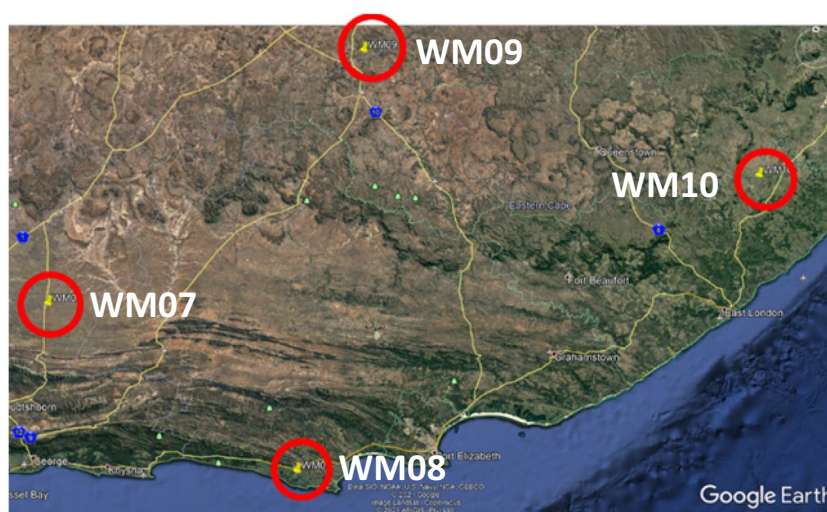


Table 1 WEF general specifications

WEF capacity (MW)	Between 148.5 and 192.5
Wind turbine generator type and nameplate capacity	3-bladed, horizontal axis, 5.5 MW
Hub height (m)	120
WTG rotor diameter (m)	155
Number of WTGs	Between 27 and 35
Assumed voltage connection level (kV)	132

zones including Southern Hemisphere westerlies, the Southern Hemisphere subtropics, and the African tropics. The coastal areas of the province are in fact a year-round rainfall zone (Engelbrecht et al. 2015), where cold fronts from the westerlies in winter alternate with thunderstorm producing weather systems in summer to bring all-year rainfall.

The most important synoptic-scale weather systems determining the provinces' climatology, in terms of both rainfall and wind, are mid-latitude cyclones, ridging high-pressure systems, cut-off lows, and tropical temperature troughs. These weather systems introduce some meso-scale circulation patterns such as Berg winds, which are also important in terms of the wind climatology.

2.4.1 Mid-latitude cyclones and cold fronts

Key to Eastern Cape's wind climatology is the frequent passage of mid-latitude cyclones in the Southern Ocean to the south, the cold fronts embedded within these systems, when occurring at sufficiently northerly latitudes, bring distinct wind patterns to the Eastern Cape. Ahead of an approaching cold front, winds are dry and from the northwest, whilst cool or cold high southwesterly winds blow behind the front. These frontal systems are positioned more Equatorward in

winter and occur more frequently and intensely during these months. They can on occasion penetrate deep into the southern African interior during 'cold snap' events, and substantially increase the energy demand in order to achieve human comfort (Tyson and Preston-Whyte 1988).

2.4.2 Ridging anticyclones

The South-Atlantic Ocean High typically ridges in behind cold fronts affecting the Cape south coast regions of South Africa, including the Cape south coast (Ndarana et al. 2020). The ridging process initially strengthens the southwesterly flow behind the cold front, but as the process continues, the flow can become pronounced southeasterly. Such ridging high-pressure systems are consequently important sources of not only wind energy for the Eastern Cape, but also of moisture and rainfall (Engelbrecht et al. 2014). Rainfall can be particularly heavy if the system co-occurs with a cut-off low (Engelbrecht et al. 2014).

2.4.3 Upper-air troughs and cut-off lows

All mid-latitude cyclones are three-dimensional weather systems, with upper air troughs typically occurring to the west of the surface cold front, and with rainfall occurring to the east of the upper air trough. When an upper air trough becomes separated or 'cut-off' from the westerly wind regime, it is referred to as a 'cut-off low'. The generally slow-moving cut-off lows are responsible for many of the flood producing rains in South Africa, including the Eastern Cape (Engelbrecht et al. 2013; Engelbrecht et al. 2015). Their frequency peaks in March to May and September to November with lower frequency between December and February (IEA 2022). Cut-off lows and upper-air troughs frequently cause several days of cloud cover, implying their indirect importance to the wind-energy sector (i.e. via

reduced solar potential). Moreover, cut-off lows are associated with pronounced southeasterly flow over the Eastern Cape (Engelbrecht et al. 2015).

2.4.4 Coastal low and Berg wind

Several meso-scale weather systems and phenomena induced by the synoptic-scale flow also impact on Eastern Cape climatology. Coastal lows form in the northwesterly flow ahead of an approaching cold front due to the generation of cyclonic vorticity when air descends from the South African plateau. They are associated with strong meso-scale pressure gradients with northwesterly flow to the east, and southwesterly flows to the southwest of the centres of these systems (Tyson and Preston-Whyte 1988).

A further mesoscale phenomenon associated with the coastal low and approaching cold front, typically occurring in winter, is the 'Berg winds' that form when northwesterly winds descend over the southern escarpment and warm adiabatically to produce high surface temperatures over the Eastern Cape. These Fohn-type winds (Tyson and Preston-Whyte 1988; Tyson 1964) occur most commonly in winter due to the relatively high frequency of passing frontal systems during this season.

2.4.5 Temperate disturbances in the westerlies

Fine-weather and mildly disturbed conditions over the Southern African interior occur in association with large subtropical high-pressure systems centred over the subcontinent. These systems produced fine clear conditions and little or no rainfall, and impact on the northern interior regions of the Eastern Cape. The frequency of occurrence of anticyclones reaches a maximum over the interior plateau in June and July with a minimum during December.

2.5 Wind farm modelling software

Two different tools, WAsP © and OpenWind ©, have been utilised to calculate the energy production at each WEF site to provide further robustness to the results. Both are industry leading tools used for wind data analysis, wind atlas creation, wind farm energy yield analysis, and siting of WTGs. Note that steps 3 and 4 in Section 3.1 can be undertaken automatically in Openwind © if input loss and uncertainty values are setup within the software.

2.5.1 WAsP ©

As per the methodology outlined in preceding sections, the linear downscaling software WAsP © has been used in a semi-manual approach to generate AEP for each site. The spatial and temporal distribution of the wind resource is

provided in the form of a wind resource grid (WRG) and uses a virtual WTG. The AEP results are then post-processed using bespoke built spreadsheet calculators (Danish Technical University n.d.-a).

The wake loss model used is Modified Park (Park 2) using a wake decay constant of 0.09 (Danish Technical University n.d.-a).

2.5.2 OpenWind ©

Calculating the expected energy production of wind turbines in an array is the basic function of Openwind © which follows in principle the same steps outlined in steps 3 to 4 of Section 3.1 and uses a mass consistent approach. The spatial and temporal distribution of the wind resource is also provided in the form of a wind resource grid and the characteristics of the WTGs with loss assumptions complete the main input elements for the calculation (Underwriter Labs n.d.).

Although there are many options, the wake loss model used is also Modified Park to remain consistent with WAsP © and uses a wake decay constant of 0.09 (Underwriter Labs n.d.).

2.5.3 Validation of the WEF modelling software

To verify that the equations and assumptions used in the OpenWind © energy production calculations, AWS Truepower has carried out a comprehensive validation exercise involving 20 real-world wind projects, using as a control the WindFarmer program of Garrad Hassan and Partners, Ltd. (Underwriter Labs (UL) 2010). A comparison of the energy production results is supplied in Section 4.2 for both WAsP © and Openwind © at the sites chosen to provide confidence that similar results are obtained from the different software.

2.6 Self-organising maps (SOMs)

To quantify the energy-meteorology climatology of the Eastern Cape Province, the approach of using SOMs is proposed. These maps are used to objectively identify the prevailing synoptic weather types occurring in the Eastern Cape Province of South Africa.

The field of climatology has widely adopted the use of SOMs, a machine learning-based approach to clustering, in recent years and was introduced to the field in 2002 (Doan et al. 2020). Kohonen originally developed SOMs (Kohonen et al. 1996) for data mining. SOMs discover patterns intrinsic to complicated input datasets and as a result can generate a cluster of simplified representations of the dataset, called nodes. The most important patterns of the input dataset are represented by the nodes (Doan et al. 2020). Synoptic weather typing is an original use of applying SOMs in climatology (Sheridan and Lee 2011) as used in several studies

over South and Southern Africa (Lennard and Hegerl 2014; Pinto et al. 2015) and elsewhere (Hewitson and Crane 2002; Hope 2006; Sammon 1969).

The algorithm used by a SOM iterates and gradually updates the makeup of the nodes in the data space until it results in a converged solution, i.e. the ‘best’ summarised representation of the input data. For each iteration, the algorithm chooses a random input vector and matches it to one of the nodes. The ‘winning’ node is called the best matching unit (BMU) (Doan et al. 2020).

Training is then carried out by adjusting the BMU and its neighbours to become closer to the input vector. The learning rate and neighbourhood function are key inputs that govern the training task. Traditional SOMs use the Euclidean distance (ED) to search for the BMU, where the ‘closest’ node to an input vector in terms of ED will be assigned as the BMU (Doan et al. 2020).

2.6.1 SOM software

The SOMPAK © software package (Kohonen et al. 1996) is one of the earliest realisations of the SOM methodology. It contains all programs necessary for the correct application of the SOM algorithm to visualise and cluster the ERA5 geopotential dataset.

2.6.2 SOM input dataset

For the purposes of this study, the fifth generation of the European Centre for Medium-Range Weather Forecast’s Atmospheric Reanalysis dataset (ERA5) (Hersbach et al. 2020; European Centre for Medium-Range Weather Forecasts, ERA5 n.d.) at six hourly and $\sim 0.28^\circ$ (TL639⁶) temporal and spatial resolution respectively has been used for the period 2010 to 2019 to correlate with the equivalent resolution wind resource and energy production data. ERA5 geopotential at 1000 hPa, converted to geopotential height by dividing with 9.81 m/s^2 , is used as the variable to characterise the 6-hourly circulation patterns.

The data covers the Earth on a $\sim 30\text{-km}$ grid and resolves the atmosphere using 137 levels from the surface up to a height of 80 km. ERA5 data is known to provide a realistic representation of African rainfall patterns (Engelbrecht and Steinkopf 2022) and likely also of the underpinning circulation patterns.

⁶ Spectral coefficients or Gaussian grids are the method in which ERA5 data is archived to provide a somewhat uniform spacing over the globe. The ERA5 high-resolution (HRES) wind resource data are archived on a reduced Gaussian linear grid and in the case of this study, the name of the grid is TL639 (European Centre for Medium-Range Weather Forecasts, ERA5 n.d.).

The domain for which the geopotential dataset was extracted spans Southern Africa (16°E to 34°E and 22°S to 35°S), with the relevant smaller Eastern Cape domain of interest contained within the larger domain. To provide a normalised input for the SOM software, so that the seasonal differences in geopotential height do not dominate the SOM-derived synoptic types, the spatial average of geopotential across the Eastern Cape domain was subtracted from the value at each ERA5 grid point. That is, the SOM is developed using the special anomalies of geopotential, following Engelbrecht et al. (2015).

3 Methodology

The proposed methodology that follows is carried out in three major steps namely:

1. Energy yield analysis:

- Step 1: Meteorological data acquisition and wind resource analysis
- Step 2: WEF modelling
- Step 3: Net AEP energy yield analysis
- Step 4: Daily energy production calculation

2. SOM training

3. Energy mapping:

- Step 1: Match energy production to each node
- Step 2: Identifying the corresponding synoptic type for each of the 35 SOM nodes

3.1 Energy yield analysis

A crucial part of the energy yield analysis for a WEF is a sufficiently long period of observed wind resource time-series, derived from measurement instruments mounted on a meteorological mast on the site. This observed wind resource data generally needs to be properly quality controlled to make sure there are no anomalies that could impact the energy production calculations.

Step 1: Meteorological data acquisition and wind resource analysis:

The typical process, also applied here, is recommended as follows:

1. Confirmation that the duration of measurement is longer than 1 year. In this case, 10 years of measured data was available to use from the WASA meteorological masts.

Note that the requirement of having data for at least 1 year is currently a general requirement of lenders and from a climatological perspective, a period of at least 20 years would have been preferred to fully characterise the inter-annual variability of weather systems.

2. Perform a visual inspection of the dataset to identify missing portions of data and remove severe outliers.
3. Make sure data availability is greater than 99% for the highest anemometers for the duration of the measurement period. If this is not achievable, then other available anemometers can be used for data filling.
4. Verify all timestamps to make sure they are consecutive.
5. Data quality control:
 - a. Remove data that is greater than 18 days corrupted.
 - b. Replace data that is corrupted for less than 18 days and greater than 1 day from alternate instruments on the meteorological mast.
 - c. Repair values corrupted for less than 1 day by using data from a previous or subsequent day or take averages of the previous and following several days or fill data/extrapolate from another anemometer.
 - d. Perform a plausible value check to make sure the measured values are within reasonable limits.
 - e. Perform a plausible rate of change check to make sure that there are no unreasonable step changes in the data.
 - f. Perform a tower shadow analysis to adjust measurements affected by the meteorological masts tower shadow.
 - g. Perform a long-term adjustment using the closest node from a long-term reanalysis dataset such as ERA5 or MERRA2.
- b. A preferred wind farm layout adhering to standard $3 \text{ rotor diameter (non-predominant wind direction)} \times 9 \text{ rotor diameter (predominant wind direction)}$ WTG spacing to minimise internal WEF wake losses.⁸
- c. A suitable virtual WTG model based on the original equipment manufacturer's (OEM's) power curve for the correct turbulence intensity, wind class, and air density at the WTG's hub height.
- d. A virtual meteorological mast which is a virtual representation of the data derived from step 1.
- e. A wind resource grid (WRG) is derived from the Wind Atlas Analysis and Application Program (WAsP) method of extrapolation (Danish Technical University n.d.-b) of the actual wind speeds at the met mast position to the actual WTG positions (Danish Technical University n.d.-a). The method of calculating the wind speeds at WTG hub height in the WAsP method makes use of a logarithmic wind profile⁹ dictated by the terrain surface roughness (Danish Technical University n.d.-a).
1. Once these items are in place, the wind farm modelling software, in some cases making use of computational fluid dynamics (CFD) in extremely complex terrain, can build the wind flow model and calculate the AEP specific to the wind farm layout, WTG, DTM, and observed wind resource data.
2. This AEP value is typically a gross value with no losses deducted and is based on a typical meteorological year (TMY) derived from the measurements and extrapolated to the WTG positions.

Step 3: Net AEP energy yield analysis:

Considering a normal distribution, the P50 energy production is the centre value and is calculated as follows:

1. The wind energy modelling software calculates the wake losses for each WTG in a WEF and thereby the part-net annual energy production of each WTG turbine, and aggregates this for the entire WEF (The Danish Technical University n.d.-b).
2. Once the gross AEP and the wake loss percentage are known, additional losses can be considered and factored into the final net AEP. These are namely the 'Balance

Similar methodologies have been employed by studies carried out globally and reinforce the use of reanalysis datasets for not only long-term correction but, where there is no measurement data, these datasets can be used as the base dataset in the quantification of the wind energy production, each of course having their unique strengths as outlined by Gruber et al (Gruber et al. 2022). Some examples of such Wind Resource Assessment methodologies can be found from Oman and Thailand in (Khan et al. 2023) and (Charabi et al. 2019).

Step 2: WEF modelling:

The fundamental components that constitute the wind farm model are outlined below, followed by the calculation procedures:

- a. An underlying digital terrain model (DTM⁷).

⁷ The digital terrain model associated with the wind farms modelled in this research contains an elevation layer derived from SRTM V.2 publicly available data, with 10-m contour height.

⁸ WEF wake losses: disturbance of the free wind speed by the WTG blades, in turn affecting the downstream wind turbines whereby the free wind speed loses some of its energy.

⁹ A logarithmic wind profile allows extrapolation of wind speeds measured at a particular height to the hub height of the WTG. The formula used is $U(z) = (u_s/K) \ln(z/z_0)$ where z is height from surface, z_0 is the roughness length, u_s^* is the friction velocity, and K is the Von Karman constant.

of Plant' (BOP) losses and are estimated based on experience and industry accepted norms, calculated where possible and taken from contractual turbine supply agreements. They are made up of the following items:

- a. WTG availability (typically ~3%)
 - b. Electrical efficiency (typically ~2%)
 - c. WTG performance (typically ~3%)
 - d. Environmental (typically ~1%)
 - e. Curtailments (typically ~1%)
3. By applying all loss factors to the gross AEP value, the net AEP can be calculated.
 4. Uncertainty: It should be noted that all the steps in such a methodology have inherent uncertainty particularly in the wind resource assessment and energy yield analysis. This can be calculated to determine probability values outside the P50, typically the P75 for lenders; however, since we are concerned only with the P50 in this study, it is not within the scope. As an indication however, the overall standard deviation of the uncertainty associated with the sites covered in this study could range from 8 to 13%.

Step 4: hourly energy production calculation:

1. The final step in the energy production process is to develop an '8760' energy production which is the annual energy at hourly resolution based on the average hourly wind speed for the wind farm for the 10-year period of interest (Frew et al. 2017).
2. Each hourly wind speed for the complete measured timeseries is passed through the WTG power curve to provide an energy production for each hour.
3. This is summed up for one year and compared to the Net AEP derived in step 3.
4. The average hourly windspeed values are then scaled to provide a matching Net AEP to that derived in step 3 thus intrinsically considering all the losses in the hourly average windspeed. This ensures that the WEF will still operate at or close to rated power for suitably high windspeeds.
5. The hourly energy production can then be adjusted to whatever resolution is required to correlate with the reanalysis data weather patterns, for example 6-hourly data from ERA5.

3.2 SOM training

Based on the work done by Engelbrecht et al. (Engelbrecht et al. 2014), who related Eastern Cape rainfall patterns to synoptic types using SOMs, it was decided to use 35 nodes (representing 35 characteristic synoptic type circulation patterns), derived from the ERA5 reanalysis dataset. The SOM was developed over the smaller Eastern Cape spatial area of interest (box in Fig. 1).

SOMPAK © was used to produce the final trained SOM for this study using the following steps:

- 1 Data preparation: SOMPAK © requires the data for input to be in a matrix $1 \times N$ format prior to execution of the algorithm. To do this, a python script was used to reshape the 2-D ERA5 dataset into a 1-D matrix for input into the SOMPAK © software.
- 2 Running the SOMPAK © software: SOMPAK © creates the data files of common synoptic type patterns needed for producing the trained SOM map. Once the SOM has been trained using a vector quantisation algorithm (Kohonen et al. 1996), i.e. the SOM with the 35 archetypical synoptic states is produced, it assigns a BMU for each timestep in the input dataset. The specifications used to run the software are as follows:
 - Lattice type: rectangular
 - Number of iterations: 100,000
 - Training: is done in two phases (1) the ordering phase during which the reference vectors of the map units are ordered; (2) the values of the reference vectors are fine-tuned.
 - Initial neighbourhood radius: 3 (decreases to 1 during training)
 - Initial learning rate parameter: 0.1 (decreases to 0 during training)
- 3 It is necessary to confirm that the SOM result makes sense by checking the Sammon maps, a 2-D representation of the n -dimensional data space (Kohonen et al. 1996). If there are folds in the map, it is difficult to interpret implying that the radius of influence variable needs to be increased.

3.3 Energy mapping

Following the process of characterising the 35 synoptic types, the resultant energy production associated for each can be quantified via an energy mapping process as follows:

Step 1: Match energy production to each node:

Table 2 Annual site wind resource characteristics at met mast height

	WM07 WEF (62 m)	WM08 WEF (62 m)	WM09 WEF (62 m)	WM10 WEF (62 m)
Annual mean wind speed- U (m/s)	6.95	7.22	8.00	6.65
Wind shear exponent (α)	0.163	0.160	0.136	0.137
Weibull k parameter	2.37	2.05	2.34	2.02
Turbulence intensity	0.12	0.12	0.11	0.12
Power density @ 50 m (W/m^2)	268	388	392	278

1. SOMPAK © makes use of Euclidean distance to determine the BMU for each timestamp in the 10-year ERA5 dataset. In this way, each timestep is mapped to a node.
2. It is then possible to map the energy produced in each correlated time step (sum of energy over the 6-h period) to the corresponding SOM node or BMU.
3. The corresponding energy production per timestep is then used to determine the best performing SOM node in terms of energy production.

Step 2: Identifying the corresponding synoptic type for each of the 35 SOM nodes:

1. The Eastern Cape Domain is too small to identify large scale drivers of the regional climate, so the timestamps associated with each node are used to extract the equivalent ERA5 geopotential (spatially normalised) timestamps for a larger spatial area including all South Africa.
2. This was then averaged per SOM node for the whole of South Africa to produce a single representative image of the synoptic type.
3. These can then be compared to commonly occurring synoptic weather types and assigned to the one that matches it the best.

4 Results and discussion

4.1 Wind resource

In summary, each of the four WEF sites has a capacity between 148.5 and 192.5 MW and employ 3-Bladed, 155-m diameter, horizontal axis, 5.5 MW WTGs at 120-m hub height.

Table 2 provides the mean wind speeds of the four wind farm sites amongst other characteristics. The mean wind speeds are typical of a class III wind site as per the IEC wind classification. This implies a good wind resource and power density.

WEF WM09, situated in the North of the EC Province, sees the highest average annual wind speeds with the other three WEFs—WM07 (Eastern EC), WM08 (Southern

EC), WM10 (Western EC)—also showing similar profiles. Wind shears tend to be quite different per site with WM07 showing the highest wind shear, i.e. the increase in wind speed with increased height. Finally, the wind speed frequency distribution's k parameter shows WM09 and WM07 have values close to 3 implying relatively stable wind speeds whereas the other two show moderately stable wind speeds. This is corroborated by the relatively low turbulence intensity values (Table 2).

Table 3 summarises the general annual, seasonal, and diurnal site characteristics for each modelled WEF's meteorological mast data. At all four of the sites, the annual average wind speeds, which vary between 7 and 8 m/s, confirm the favourable wind potential that exists across the Eastern Cape. At three of the four sites, most months exhibit the strongest winds around midday. This is likely the consequence of the land-sea temperature gradient being at its strongest around midday, which contributes to enhanced pressure-gradients and high wind speeds. The exception is site WM07, where most months exhibit the strongest wind speeds at night.

At sites WM09 and WM10, average monthly wind speeds peak in winter and remain relatively high in summer. Closer to the coast at site WM08, wind speeds peak in spring and summer but remain relatively high in autumn and winter. At site WM07 over the western interior, autumn and spring are seasons with high wind speeds at night, but with winter recording high values on the average right through the diurnal cycle.

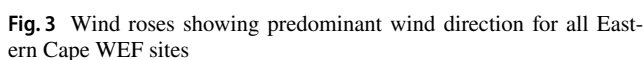
The wind roses (Fig. 3) indicating the predominant wind direction at the near-coastal site (WM08) and western interior site (WM07) predominantly swing between easterlies and westerlies. At site WM09 over the northern interior, wind direction predominantly swings between north westerlies and south easterlies. At site WM10 over the north-eastern interior, there is a more uniform distribution of wind directions, with slightly higher frequencies from the northeast.

WM07 WEF

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	2000-01
00:00-01	8.813	8.222	7.881	7.54	7.185	7.583	7.897	7.694	7.4	7.863	8.248	8.3	7.679
01:00-02	8.002	7.821	7.513	7.087	7.041	7.585	7.907	7.487	7.64	7.508	7.89	7.754	7.623
02:00-03	7.504	7.47	7.07	7.131	6.944	6.956	7.384	7.305	7.412	7.487	8.029	7.763	7.414
03:00-04	7.189	7.039	6.765	6.789	6.739	7.127	7.297	7.299	7.391	7.501	7.918	7.938	7.143
04:00-05	6.945	6.784	6.504	6.528	6.478	6.866	7.036	7.038	7.184	7.284	7.759	7.784	6.949
05:00-06	6.646	6.477	6.183	6.201	6.128	6.518	6.689	6.701	6.848	6.974	7.318	7.343	6.478
06:00-07	6.156	6.136	5.814	5.928	5.833	6.138	6.31	6.308	6.503	6.477	6.772	6.772	6.183
07:00-08	5.851	5.793	5.721	5.717	5.628	5.947	6.078	6.078	6.265	6.265	6.561	6.561	5.828
08:00-09	5.545	5.487	5.409	5.405	5.316	5.595	5.742	5.742	5.929	5.929	6.225	6.225	5.545
09:00-10	5.198	5.131	5.116	5.022	5.003	5.288	5.434	5.434	5.619	5.619	5.903	5.903	5.198
10:00-11	4.744	4.685	4.679	4.581	4.568	4.825	4.948	4.948	5.132	5.132	5.416	5.416	4.744
11:00-12	4.851	4.786	4.782	4.681	4.671	4.931	5.053	5.053	5.237	5.237	5.521	5.521	4.851
12:00-13	5.174	5.095	5.062	4.959	4.958	5.195	5.318	5.318	5.502	5.502	5.812	5.812	5.174
13:00-14	5.478	5.389	5.356	5.253	5.253	5.491	5.614	5.614	5.798	5.798	6.108	6.108	5.478
14:00-15	5.967	5.786	5.814	5.683	5.644	5.988	6.111	6.111	6.295	6.295	6.605	6.605	5.967
15:00-16	6.414	6.289	6.302	6.088	6.167	6.471	6.594	6.594	6.778	6.778	7.088	7.088	6.414
16:00-17	6.817	6.673	6.686	6.482	6.561	6.865	6.988	6.988	7.172	7.172	7.482	7.482	6.817
17:00-18	7.189	7.025	7.038	6.834	6.913	7.217	7.34	7.34	7.524	7.524	7.834	7.834	7.189
18:00-19	8.463	8.129	7.945	7.665	7.594	8.332	8.505	8.505	8.689	8.689	8.999	8.999	8.463
19:00-20	8.208	8.089	7.983	7.622	7.632	8.066	8.238	8.238	8.422	8.422	8.732	8.732	8.208
20:00-21	8.122	8.003	7.943	7.717	7.644	8.136	8.308	8.308	8.492	8.492	8.802	8.802	8.122
21:00-22	8.002	7.883	7.823	7.597	7.524	8.016	8.188	8.188	8.372	8.372	8.682	8.682	8.002
22:00-23	7.882	7.763	7.703	7.477	7.404	7.896	8.068	8.068	8.252	8.252	8.562	8.562	7.882
23:00-00	7.882	7.682	7.622	7.396	7.323	7.816	7.988	7.988	8.172	8.172	8.482	8.482	7.882

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	All
2004 - 01.00	1.019	1.023	1.034	1.044	1.054	1.070	1.134	1.209	1.300	1.390	1.476	1.559	1.188
2004 - 01.00	1.007	1.018	1.030	1.040	1.050	1.070	1.147	1.230	1.325	1.422	1.509	1.621	1.164
2005 - 01.00	1.019	1.030	1.040	1.050	1.060	1.070	1.130	1.210	1.300	1.390	1.476	1.559	1.188
2005 - 01.00	1.007	1.018	1.030	1.040	1.050	1.070	1.147	1.230	1.325	1.422	1.509	1.621	1.164
2006 - 01.00	1.019	1.030	1.040	1.050	1.060	1.070	1.130	1.210	1.300	1.390	1.476	1.559	1.188
2006 - 01.00	1.007	1.018	1.030	1.040	1.050	1.070	1.147	1.230	1.325	1.422	1.509	1.621	1.164
2007 - 01.00	1.019	1.030	1.040	1.050	1.060	1.070	1.130	1.210	1.300	1.390	1.476	1.559	1.188
2007 - 01.00	1.007	1.018	1.030	1.040	1.050	1.070	1.147	1.230	1.325	1.422	1.509	1.621	1.164
2008 - 01.00	1.019	1.030	1.040	1.050	1.060	1.070	1.130	1.210	1.300	1.390	1.476	1.559	1.188
2008 - 01.00	1.007	1.018	1.030	1.040	1.050	1.070	1.147	1.230	1.325	1.422	1.509	1.621	1.164
2009 - 01.00	1.019	1.030	1.040	1.050	1.060	1.070	1.130	1.210	1.300	1.390	1.476	1.559	1.188
2009 - 01.00	1.007	1.018	1.030	1.040	1.050	1.070	1.147	1.230	1.325	1.422	1.509	1.621	1.164
2010 - 01.00	1.019	1.030	1.040	1.050	1.060	1.070	1.130	1.210	1.300	1.390	1.476	1.559	1.188
2010 - 01.00	1.007	1.018	1.030	1.040	1.050	1.070	1.147	1.230	1.325	1.422	1.509	1.621	1.164
2011 - 01.00	1.019	1.030	1.040	1.050	1.060	1.070	1.130	1.210	1.300	1.390	1.476	1.559	1.188
2011 - 01.00	1.007	1.018	1.030	1.040	1.050	1.070	1.147	1.230	1.325	1.422	1.509	1.621	1.164
2012 - 01.00	1.019	1.030	1.040	1.050	1.060	1.070	1.130	1.210	1.300	1.390	1.476	1.559	1.188
2012 - 01.00	1.007	1.018	1.030	1.040	1.050	1.070	1.147	1.230	1.325	1.422	1.509	1.621	1.164
2013 - 01.00	1.019	1.030	1.040	1.050	1.060	1.070	1.130	1.210	1.300	1.390	1.476	1.559	1.188
2013 - 01.00	1.007	1.018	1.030	1.040	1.050	1.070	1.147	1.230	1.325	1.422	1.509	1.621	1.164
2014 - 01.00	1.019	1.030	1.040	1.050	1.060	1.070	1.130	1.210	1.300	1.390	1.476	1.559	1.188
2014 - 01.00	1.007	1.018	1.030	1.040	1.050	1.070	1.147	1.230	1.325	1.422	1.509	1.621	1.164
2015 - 01.00	1.019	1.030	1.040	1.050	1.060	1.070	1.130	1.210	1.300	1.390	1.476	1.559	1.188
2015 - 01.00	1.007	1.018	1.030	1.040	1.050	1.070	1.147	1.230	1.325	1.422	1.509	1.621	1.164
2016 - 01.00	1.019	1.030	1.040	1.050	1.060	1.070	1.130	1.210	1.300	1.390	1.476	1.559	1.188
2016 - 01.00	1.007	1.018	1.030	1.040	1.050	1.070	1.147	1.230	1.325	1.422	1.509	1.621	1.164
2017 - 01.00	1.019	1.030											

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	All
2000-01	7.174	7.115	7.044	6.98	6.93	7.776	8.893	8.434	8.387	7.458	7.445	7.588	7.7
2001-02	7.219	6.938	6.887	6.784	6.721	7.641	8.641	8.447	8.3	7.594	7.589	7.582	7.608
2002-03	7.01	6.823	6.73	6.651	6.54	7.308	8.028	8.434	8.376	7.594	7.37	7.184	7.534
2003-04	6.884	6.656	6.573	6.451	6.329	7.138	7.848	8.257	8.164	7.388	7.271	7.088	7.148
2004-05	6.88	6.68	6.597	6.475	6.353	7.167	7.878	8.287	8.194	7.416	7.3	7.116	7.166
2005-06	6.812	6.499	6.382	6.259	6.144	6.944	7.653	8.072	8.157	7.404	7.197	7.13	7.352
2006-07	6.816	6.547	6.483	6.347	6.217	7.031	7.832	8.268	8.463	7.701	7.388	7.088	7.588
2007-08	6.956	6.637	6.487	6.329	6.18	6.988	7.698	8.136	8.343	7.584	7.218	6.935	7.418
2008-09	6.985	6.588	6.462	6.303	6.144	6.948	7.658	8.076	8.268	7.516	7.148	6.868	7.318
2009-10	6.988	6.588	6.462	6.303	6.144	6.948	7.658	8.076	8.268	7.516	7.148	6.868	7.318
2010-11	6.817	6.73	7.052	7.338	7.623	8.273	8.783	8.737	8.737	8.247	7.873	7.768	7.878
2011-12	6.688	6.688	7.088	7.488	7.887	8.187	8.188	8.088	8.088	7.588	7.488	7.388	7.188
2012-01	6.778	7.148	7.488	7.823	8.1	8.101	8.108	8.008	8.008	7.578	7.481	7.321	7.421
2013-02	6.778	7.148	7.488	7.823	8.1	8.101	8.108	8.008	8.008	7.578	7.481	7.321	7.421
2014-03	6.778	7.148	7.488	7.823	8.1	8.101	8.108	8.008	8.008	7.578	7.481	7.321	7.421
2015-04	6.778	7.148	7.488	7.823	8.1	8.101	8.108	8.008	8.008	7.578	7.481	7.321	7.421
2016-05	6.778	7.148	7.488	7.823	8.1	8.101	8.108	8.008	8.008	7.578	7.481	7.321	7.421
2017-06	6.778	7.148	7.488	7.823	8.1	8.101	8.108	8.008	8.008	7.578	7.481	7.321	7.421
2018-07	6.778	7.148	7.488	7.823	8.1	8.101	8.108	8.008	8.008	7.578	7.481	7.321	7.421
2019-08	6.778	7.148	7.488	7.823	8.1	8.101	8.108	8.008	8.008	7.578	7.481	7.321	7.421
2020-09	6.778	7.148	7.488	7.823	8.1	8.101	8.108	8.008	8.008	7.578	7.481	7.321	7.421
2021-10	6.778	7.148	7.488	7.823	8.1	8.101	8.108	8.008	8.008	7.578	7.481	7.321	7.421
2022-11	6.778	7.148	7.488	7.823	8.1	8.101	8.108	8.008	8.008	7.578	7.481	7.321	7.421
2023-12	6.778	7.148	7.488	7.823	8.1	8.101	8.108	8.008	8.008	7.578	7.481	7.321	7.421

[illegible]

The P50 annual energy production (AEP) per site is consistent with the wind resource assessment results provided (Table 2). WM09 (41.5% and 42.1%) and WM08 (41.6% and 42.0%) are providing the highest energy production figures and net capacity factors (NCF's) from WASP © and Openwind © respectively (Fig. 4). WM10 (37.2% and 37.4%) and WM07 (41.8% and 41.3%) WEF sites produce somewhat less energy. In general, the WASP © and Openwind

The P50 monthly energy production per site (Fig. 5) shows WM09 providing the highest energy production across the four sites, particularly so in the winter months. The WEF sites generally show higher production in the winter months at WM07, WM09, and WM10. At site WM08, the near coast location, the highest production is simulated for spring.

Following Engelbrecht et al. (2015), a 35 node SOM has been developed to characterise the low-level synoptic circulation types of the Eastern Cape domain (Fig. 6) using 1000-hPa geopotential height anomalies.

The top-left corner-node of the SOM (node 29, Fig. 6) shows negative geopotential anomalies to the south of the Eastern Cape, and over the southern part of the Eastern Cape, with positive anomalies over the northern interior. This pattern is due to a mid-latitude cyclone approaching from the west (Fig. 7). The bottom-right corner of

Fig. 4 P50 annual net energy production and net capacity factor per WEF from Openwind © and WAsP ©

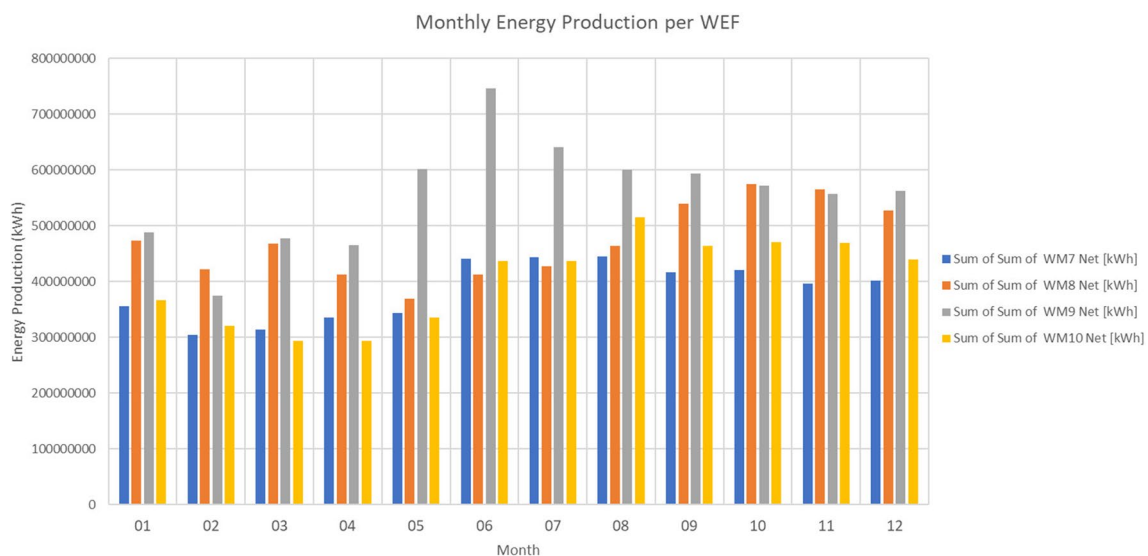
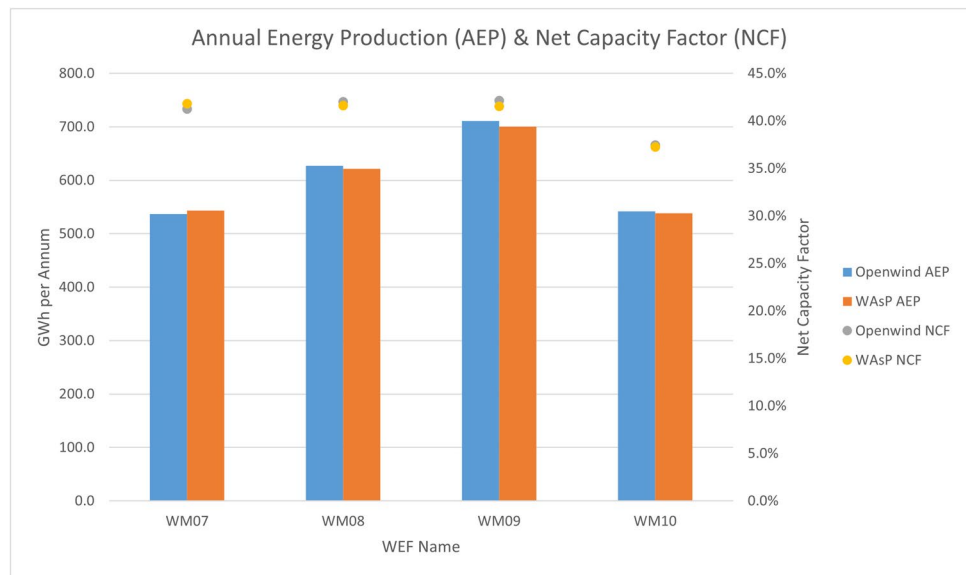


Fig. 5 P50 monthly energy production per modelled WEF site

the SOM (node 7, Fig. 6) shows the ‘opposite pattern’, positive geopotential anomalies south of and over the southern Eastern Cape, with negative anomalies over the northern interior. This pattern is the consequence of the Atlantic Ocean High starting to ridge along the Cape south coast (Fig. 7). The bottom-left corner of the SOM (node 1, Fig. 6) shows positive geopotential anomalies over the western part of the domain, with negative anomalies to the east. This is due to the Atlantic Ocean High ridging behind a steep trough and cold front (Fig. 7). The ‘opposite’ pattern appears in the top-right corner of the SOM (node 35, Fig. 6). It is the result of the Atlantic Ocean High ridging further to the east over the South African east coast, with

a deep surface trough present over the western interior regions of South Africa.

Because each 6-hourly circulation pattern occurring in the 10-year period is associated with one of the SOM nodes, the energy production of that 6-h period can be mapped onto the relevant node for each of the WEF sites. In this way, it is possible to calculate the energy production associated with each node (Figs. 8 and 9). When ranking the energy production across nodes using Figs. 8 and 9, SOM nodes 8, 15, and 1 (red outline, Figs. 6, 7, and 8) show the largest potential for energy production. All three of these nodes are characteristic of various stages of a deep mid-latitude cyclone passing to the south of the Eastern Cape, with the Atlantic Ocean High ridging behind the cold front over the Eastern Cape.

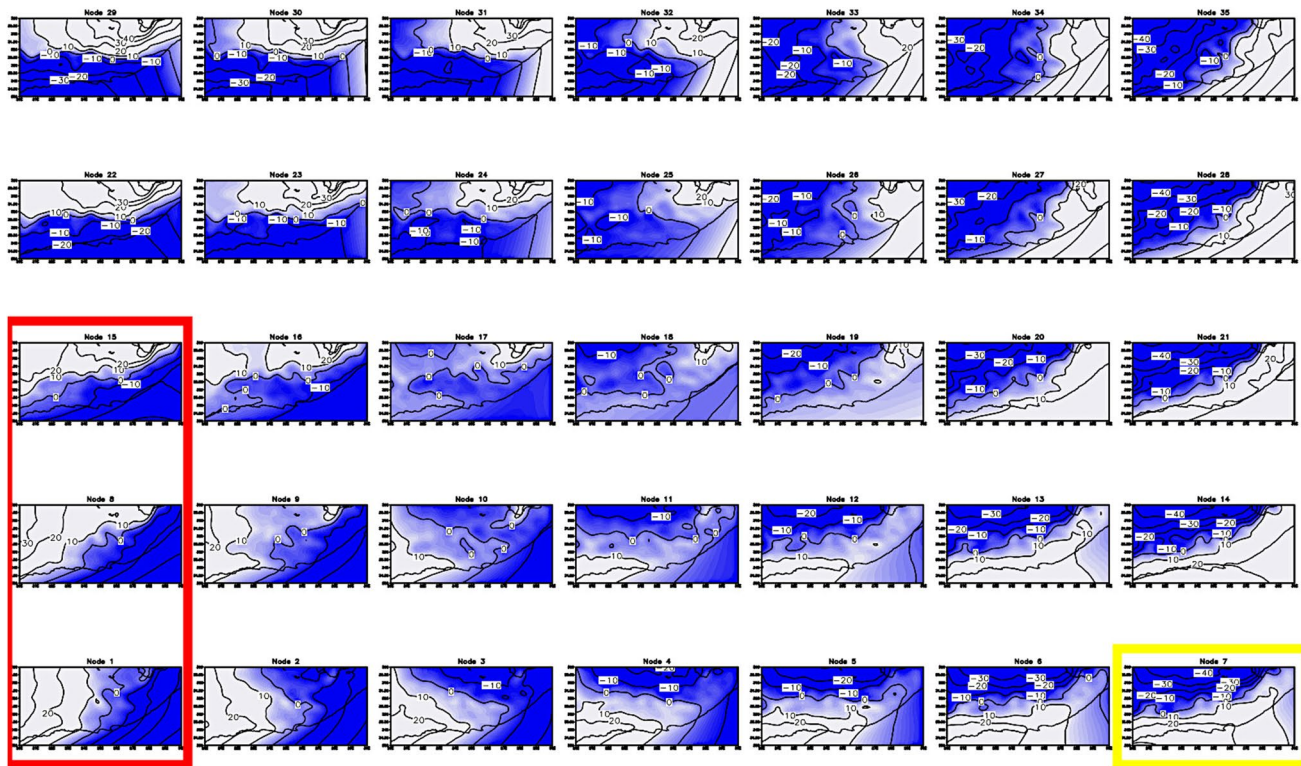


Fig. 6 35-node SOM for geopotential height anomalies in metres (red = top 3 energy producing nodes, yellow = lowest energy producing node) representing 35 low-level circulation types for the Eastern Cape (20° to 30°E ; -30° to -35°S)

To explore in more detail (Fig. 8) the seasonality of energy production in the Eastern Cape, the monthly energy production per node is shown (January to February, JFM, row 1; April to June, AMJ, row 2; June to September, JAS, row 3, October to December, OND, row 4). From this analysis, the three nodes with the highest energy potential contribute most to annual production during the winter months (June to August). This is not surprising, given that these nodes are associated with the passage of cold fronts over the Eastern Cape that occur in association with steep pressure gradients caused by the Atlantic Ocean High (Figs. 6 and 7).

Figure 9 shows the average wind speed direction per trained SOM node (averaged across the Eastern Cape domain). Consistent with the wind rose calculated for each of the sites (Fig. 3), the analysis shows the importance of predominantly westerly and easterly wind components for wind energy production in the Eastern Cape. The nodes associated with the highest energy production (marked in red, nodes 8, 15, and 1) have wind directions of $\sim 225^{\circ}$, consistent with the marked pressure gradients when the Atlantic Ocean High ridges behind a cold front. For all these cases, the Atlantic High's centre is at 30°S or further to the north (Fig. 11a to c), which is indicative of the importance of northward displaced synoptic-scale circulation patterns for optimal wind energy production in the Eastern Cape.

The annual frequency distribution map of SOM nodes is shown in Fig. 10. The SOM methodology functions in such a way that the distribution of constituting cases per node is relatively uniform across nodes. Figure 10 also indicates the average energy production per day per node which provides a reasonable proxy by which to compare the strength of each node to provide wind energy (again noting high energy producing nodes 1, 8, and 15).

4.4 Highest wind energy production nodes

To gain further qualitative insights into the energy meteorology of the Eastern Cape, we explore the synoptic patterns (Fig. 7) associated with the best and worst energy producing Eastern Cape circulation types (Fig. 6) in more detail in Fig. 11.

The patterns displayed for the top three energy producing circulation types (nodes 8, 15, and 1, Fig. 11a–c), as noted before, are indicative of the Atlantic Ocean High with a centre near 30°S ridging behind a cold front and an associated mid-latitude cyclone passing to the south of the country. For all three cases, the net result is pronounced southwesterly flow over the Eastern Cape, parallel to the geopotential height contours, and reinforcing the importance of strong

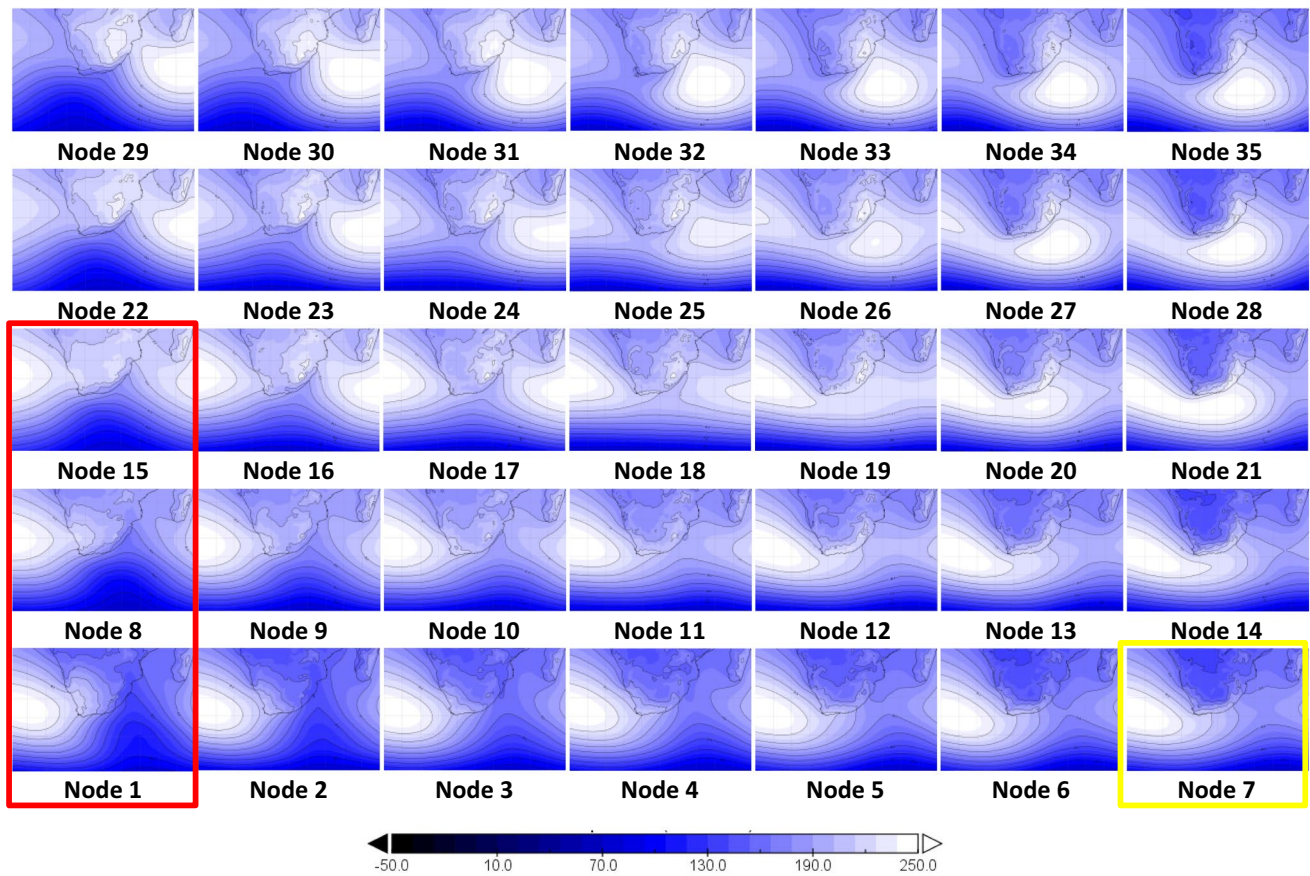


Fig. 7 Accompanying synoptic pattern (geopotential height anomalies in metres) per SOM node (Fig. 6)) (0° to 50° E; -10° to -50° S)

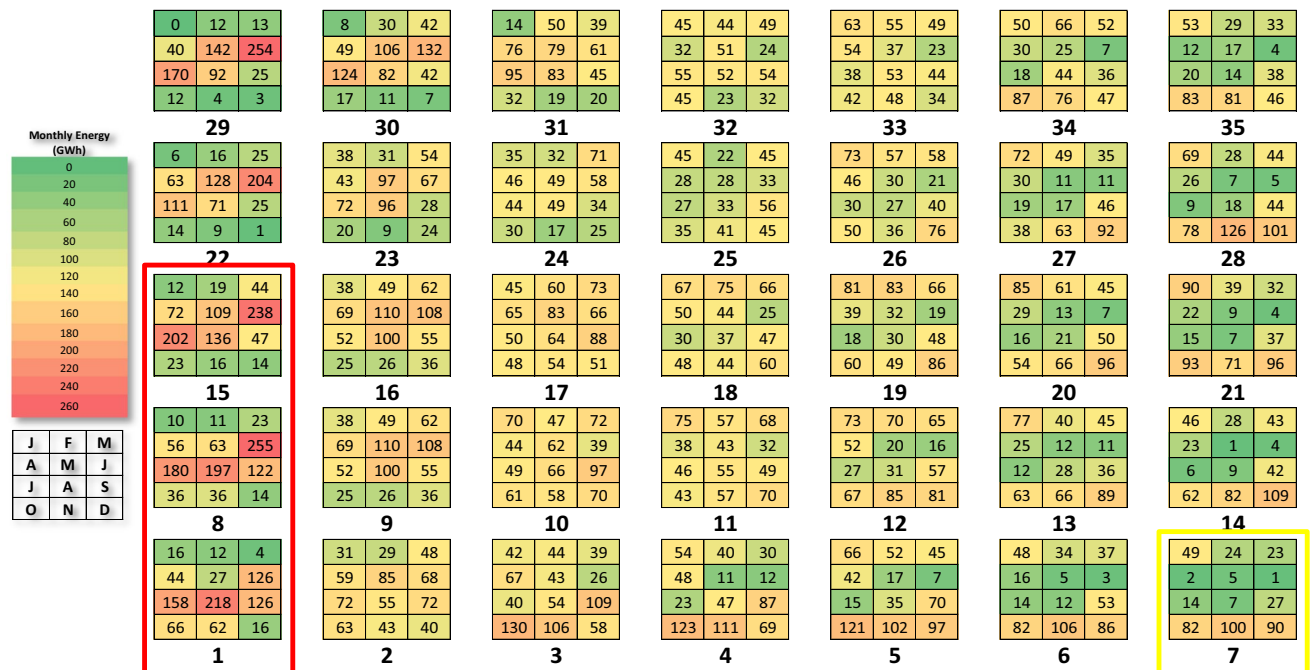


Fig. 8 Monthly total energy distribution per node summed for all four WEF sites (GWh)

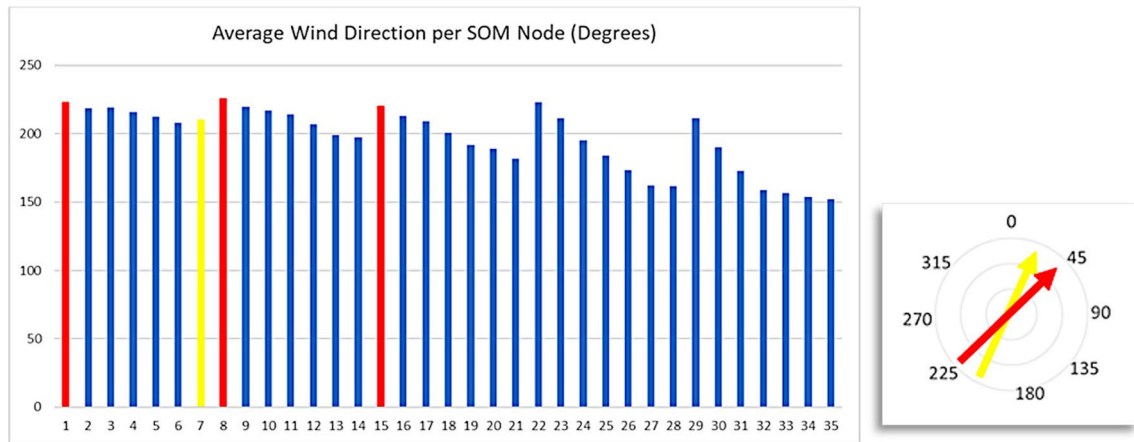


Fig. 9 Average wind direction in degrees from North per trained SOM node

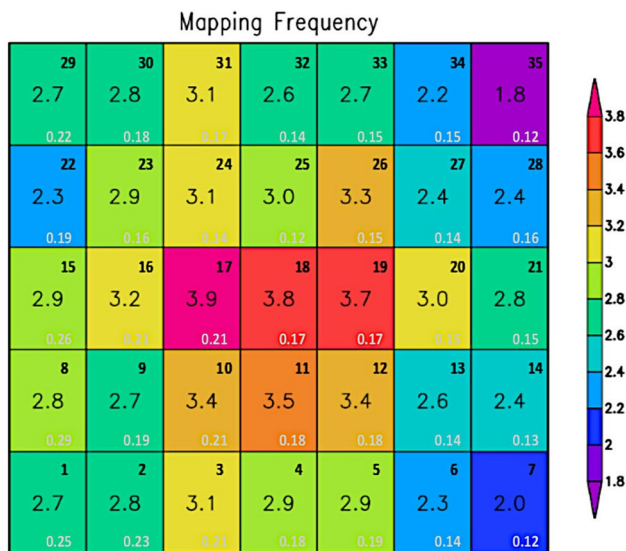


Fig. 10 Trained SOM node annual frequency map (including energy in GWh/day below each frequency), node number in top right corner

southwesterlies for wind energy generation in the Eastern Cape.

A similar study is carried out by Cheneka et al. (2021) and investigates the impact of various weather systems on the Belgian offshore wind fleet energy production using SOMs. In its conclusion, the high wind energy producing SOM nodes display similar characteristics to those identified in this study, i.e. they are characterised by low-pressure systems in front of ridging high-pressure systems similar to the mid-latitude cyclones observed in South Africa (Cheneka et al. 2021).

The circulation type and associated synoptic pattern that has the lowest energy generation potential for the Eastern Cape, node 7 (Fig. 11d), represents mid-latitude cyclones with a more poleward location and a weak ridging high

pressure with centre at about 35°S. Pressure gradients are consequently weak over the Eastern Cape, and wind energy production is low.

5 Conclusions

For South Africa to pursue a Just Energy Transition out of its heavy dependence on coal, it needs to increasingly invest in the country's rich resources in wind and solar energy. The Eastern Cape Province has a very high potential for wind energy production and in this research, we explore the relevant energy meteorology and its seasonality in more detail.

The foundation for the study is the long-term meteorological wind mast measurement data available from WASA for four sites in the Eastern Cape, which enabled the calculation of annual and seasonal energy production at four representative locations, in the Eastern Cape. For these energy yield analyses, realistic WEF and WTG designs at each of the four sites are used and run using different software to derive the wind energy production results. The four sites provide good coverage and are representative of the spatial area's energy production potential.

At each of the four sites, annual average wind speeds vary between 7 and 8 m/s, indicating a potentially high wind resource. The energy yield analysis reveals the importance of winter as the season with the highest energy potential. This is not a surprising result, given the northward passage of mid-latitude cyclones over the Southern Ocean in winter. Generally, energy production is the highest around midday and the afternoon, likely because the ocean temperature gradient is then at its steepest, strengthening the pressure gradients and winds.

Following the energy yield analysis, a 35 node SOM was generated to identify the prevailing circulation types of the Eastern Cape, using ERA5 reanalysis data at 6-hourly

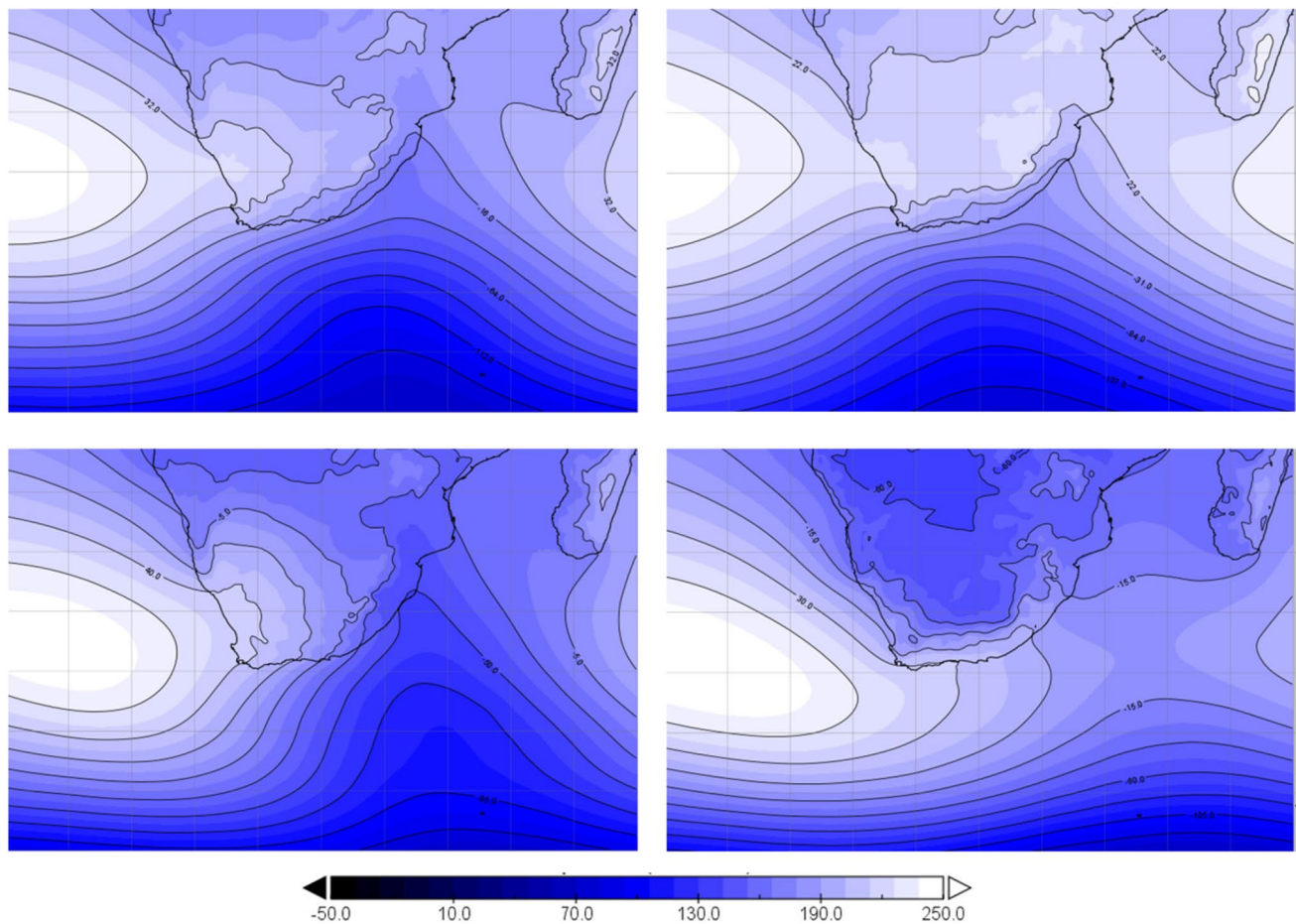


Fig. 11 (a) Trained SOM nodes 8, (b) 15, (c) 1, and (d) 7 the greater synoptic pattern 0° to 50°E ; -10° to -50°S (geopotential height in metres reduced by spatial average of geographical focus area)

resolution. This SOM result is then mapped onto the 6-hourly P50 energy production. Van Aarde et al. in 2023 follow a similar methodology for South Africa, focusing on resource potential (van Aarde et al. 2023) without taking the next step of providing detailed energy modelling methodologies and results. This study is hereby the first to quantify the energy meteorology of the Eastern Cape, by objectively exploring the detailed P50 energy production of different synoptic types.

The SOM analysis reveals that the synoptic-circulation pattern with the highest energy potential for the Eastern Cape is the Atlantic Ocean ridging high with its centre at about 30°S , behind a northward displaced mid-latitude cyclone. This results in steep pressure gradients and predominantly south-westerly winds over the Eastern Cape. However, when mid-latitude cyclones pass over the Southern Ocean further to the south, and the Atlantic Ocean High ridges with its centre further to the south at about 35°S , pressure gradients and energy production are weakest.

SOM nodes 8, 15, and 1 (red outline, Figs. 6, 7, and 8) show the largest potential for energy production. All three

of these nodes are characteristic of various stages of a deep mid-latitude cyclone passing to the south of the Eastern Cape, with the Atlantic Ocean High ridging behind the cold front over the Eastern Cape. These three nodes with the highest energy potential contribute most to annual production during the winter months (June to August) and have predominant wind directions of $\sim 225^{\circ}$, consistent with the marked pressure gradients when the Atlantic Ocean High ridges behind a cold front.

The methodology developed here, linking energy production at WEF sites to archetypal synoptic types identified by the SOM, provides the foundation for the prediction of wind energy production at various timescales. Particularly, for seasonal forecasts and climate change projections using GCMs whose spatial resolution is relatively low.

This method can be applied to an ensemble of GCMs to project future energy potential through the lens of projected changes in synoptic type frequencies. These changes, in combination with the energy potential associated with the different synoptic types, will effectively yield predictions of future wind energy production. Applications could

include improved understanding of the long-term viability of wind farm sites, guidance on renewable energy development zones, technology selection, and integrated resource planning.

Author contribution All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by GL and supported by FE and CL. The first draft of the manuscript was written by GL and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding Open access funding provided by University of the Witwatersrand. This work was supported by the National Research Foundation of South Africa through its Earth System Science Research Programme, Grant 118598.

Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests The authors declare no competing interests.

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