Integration of Non-Programmable Renewable Energy

in the National Electric System of South Africa



RES4AFRICA FOUNDATION

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About RES4Africa

RES4Africa Foundation's (Renewable Energy Solutions for Africa) mission is to create an enabling environment for scaling up investments to accelerate a just energy transition and transformation. It gathers a member network from across the clean energy value chain and supports the creation of an enabling environment for renewable energy investments and strategic partnerships. See more: www.res4africa.org

About the Sub-Saharan Programme

RES4Africa's Sub-Saharan (SSA) Programme works to support the region to maximize its green energy potential, creating an enabling environment for the implementation of RE projects to drive the just energy transformation of sub-Saharan African countries. Building a regulatory and legislative environment which favours RES projects and attracts private investments is key in driving the regional energy transition: to achieve these goals, R4A continuously works to address the key issues of the area, adapting and developing its actions to suit local needs through advocacy, reports, studies and training programmes.

With a permanent office in Johannesburg, the Programme gives special attention to South Africa. RES4Africa aims to contribute to the roadmap design for an effective and just energy transition in the country. The programme dedicates conferences and studies to breaking down key issues and discussing options for the sustainable development of the power sector. In partnership with local partners and stakeholders, the Foundation also carries out as three showcase initiatives: AM-Powering Connexions, Re-Skilling Lab and Executive seminars.

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ABBREVIATIONS

CAGR	Compound Annual Growth Rate
CAPEX	Capital Expenditure
CF	Capacity Factor
CSIR	Council for Scientific and Industrial Research
GCCA	Generation Connection Capacity Assessment
GHI	Global Horizontal Irradiation
GTI	Global Tilted Irradiation
IEC	International Electrotechnical Commission
IPP	Independent Power Producer
IRP	Integrated Resource Plan
KPI	Key Performance Indicators
LCOE	Levelized Cost of Electricity
NES	National Electricity System
NOCT	Nominal Operating Cell Temperature
OCGT	Open Cycle Gas Turbine
OPEX	Operating Expenditure
PVOUT	Photovoltaic Power Output
REIPPPP	Renewable Energy Independent Power Producer Procurement Programme
S/S	Electrical Substation
SAWEA	South African Wind Energy Association
SEA	Strategic Environmental Assessment
TDP	Transmission Development Plan
V-RES	Variable Renewable Energy Sources (solar and wind)
WACC	Weighted Average Cost of Capital
WASA	Wind Atlas for South Africa

SYMBOLS

Ⓢ	Subject to sensitivity analysis
A	Weibull wind scale parameter
D	Diameter of wind turbines
f(v)	Probability density function of wind velocity
F(v)	Cumulative distribution function of wind velocity
k	Weibull wind shape parameter
kWh	Kilowatt-hour
kWp	Kilowatt-peak (i.e., when the power refers to the maximum nominal capacity)
m^2	Square meter
m/s	Meters per seconds
P_{nom}	Nominal Power
PR	Performance Ratio
T_{amb}	Ambient Temperature
v-cut_in	Minimum wind speed at which a turbine starts producing
v-cut_out	Maximum wind speed at which a turbine stops producing
v-rated	Wind velocity at which the turbine starts producing at rated power
α	Shear coefficient
η	Efficiency of PV modules at standard conditions
°C	Celsius degree

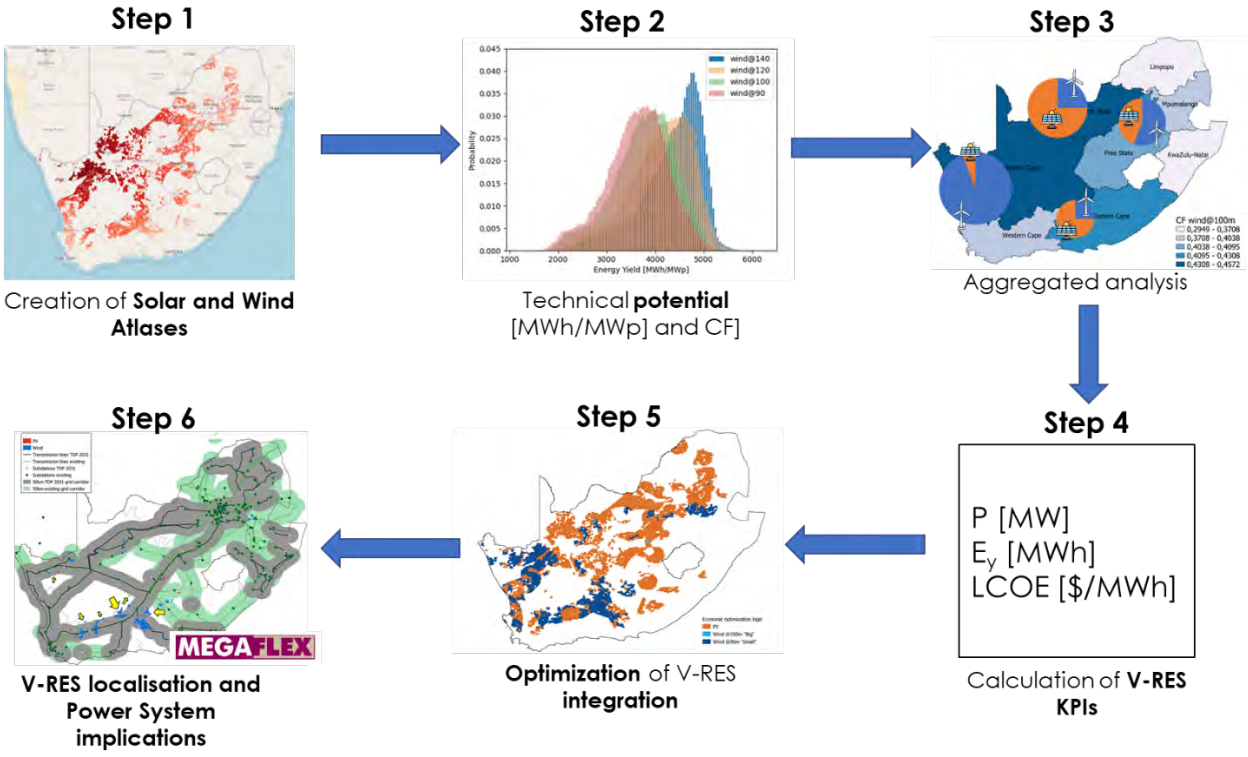
EXECUTIVE SUMMARY

According to the latest South African Integrated Resource Plan (IRP) 2010–2030 (2019 edition), around 20 GW of new non-programmable renewable energy sources (V-RES) capacity will be commissioned by 2030. Such amount of variable renewable generation needs to be integrated into the power system implementing adequate actions aimed at assuring the system security and reliability. The Project aims at contributing to meet the IRP targets by facilitating the integration of V-RES, namely solar and wind, into the South African national electricity system (NES). The specific objective of this activity is to perform a geospatial analysis aimed at exploring the **value of V-RES** (i.e., solar and wind) in South Africa. More in detail, the estimation of V-RES value concerns the following aspects:

- **Potential:** expected specific Yield [kWh/kWp] of V-RES with high spatial resolution.
- **Exploitability**: candidate V-RES generation is proposed for each spatial element, to identify the optimal maximum capacity and production.
- **Economics**: calculation of Levelized Cost of Energy (LCOE) for V-RES with high spatial resolution.
- **Viability**: investigation of locations of high-RE potential considering the expected yield of the RE resources, giving priority to the areas with the lowest cost of electricity, higher production, and proximity to the existing and planned grid.
- **Impact**: evaluation of the grid implications of V-RES exploitability in the current and expected evolution of the South African power system, as well as on the current electricity tariff. Any quantitative consideration on the impact of the results on the operation of the South African Transmission Grid are excluded from the analysis, since it would require appropriate network studies that are out of the scope of this study, as agreed upon with RES4Africa first, and also shared with Eskom.

These results are supposed to support Eskom in the identification of the most appropriate grid connection options and the grid planning opportunities for the next decade.

To achieve this goal, a 6-Steps methodology has been developed and implemented, as graphically reported in the figure below.



Each Step is characterized by the following activities and outputs reported below. The main outcomes and insights are highlighted in grey boxes. Also, the items in brackets "(Ⓢ)" refer to the results obtained by changing some quantitative hypotheses in a sensitivity analysis, based on the experience of RES4Africa (through developers) in South Africa. The parameters subject to the sensitivity analysis are:

- *Land occupation (PV)*: 2.5 ha/MW → 1.6 ha/MW
- *CF/Energy Yield, scale-up factor*: +23% for Solar on all the territory (to test the efficiency improvement deploying bifacial modules combined with tracking system) and - 18% (on average, differentiated by Province) to smooth the differences with the ESMAP Global Wind Atlas.
- *CAPEX*: 800 $/kW → ca. 676 – 780 $/kW for solar, and 1000-1350 $/kW → ca. 936 – 1248 $/kW for wind.
- *OPEX*: 9.5 $/kW/year → ca 15. $/kW/year for solar, and 2.7% of CAPEX → ca. 25 $/kW/year for wind.
- *Project Lifetime (Wind)*: 20 years → 25 years

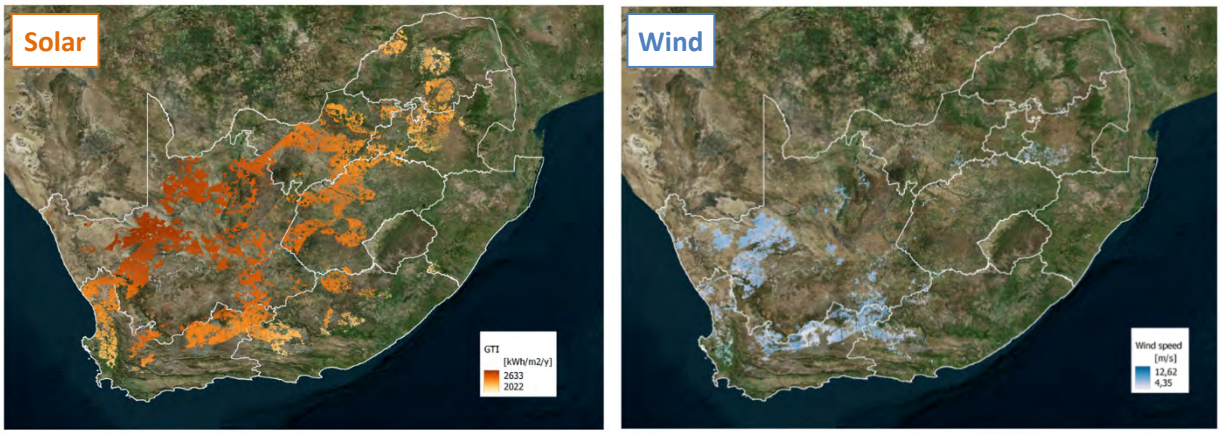
Step 1: Geospatial Data Collection and Creation of Solar and Wind Atlases

The goal of the first step of the study is the creation of V-RES Atlases reporting the renewable resources potential in South Africa excluding the unfeasible zones, i.e., the areas where it would not be possible to deploy large scale V-RES based plants due to physical and regulatory constraints. Data and information have been derived from the Global Solar Atlas of the World Bank, WASA database, and the SEA study form the CSIR. The V-RES potential, which can be defined as a bounded theoretical potential, is expressed in terms of useful indicators, representative of the amount of energy provided by the V-RES per unit surface area: for the solar resource indicators are related to solar irradiation while for wind resource indicators are related to the average wind speed that determines the energy extractable from wind turbines.

Outcomes - Step 1

From Step 1, the following considerations can be derived:

- **Solar**: solar irradiation is well distributed in the whole Admissible areas of country, providing large solar potential. The region with the largest solar potential is Northern Cape province, which is also the region with the largest (in absolute terms) territory that may host solar fields. In the province, there are areas where global solar irradiation at optimum tilt angle exceeds 2.5 MWh/m^2 per year.
- **Wind**: the Admissible areas for wind resource are limited mainly to the Northern and Western Capes. Moreover, with respect to solar, wind availability is much less uniformly distributed in the areas, ranging from locations where the average wind speed exceeds 12 m/s up to locations characterized by much lower values, close to 4 m/s.

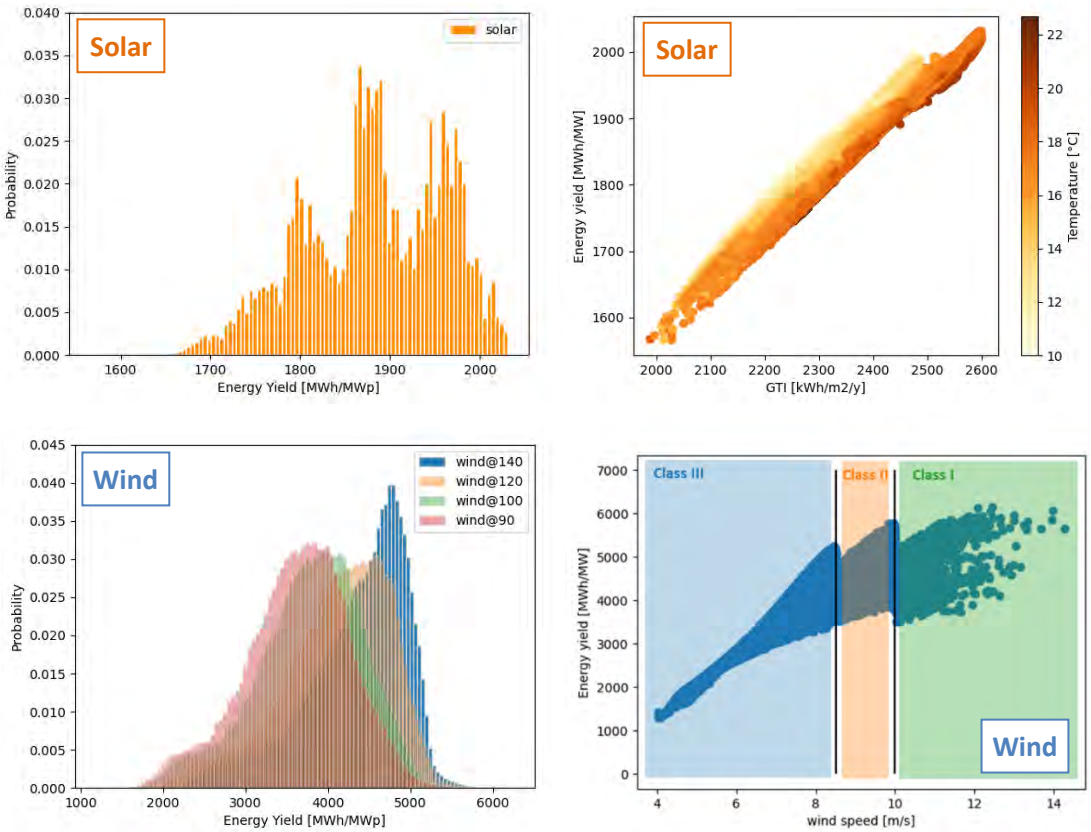


Step 2: Identification of Resources Technical Potential (Capacity Factor Assessment)

The goal of the second step of the procedure is to evaluate the technical potential, in terms of capacity factor (CF) and annual specific energy yield per unit of power capacity installed [kWh/kWp] of solar and wind resources in the Admissible areas of South Africa. The technical potential depends on the design parameters of the components used to convert solar and wind energy into electrical energy (namely photovoltaic modules and wind turbines) which need to be integrated in the Atlases creation. That is the reason why PV and wind turbines technology characteristics have been considered to derive the exploitability of V-RES during the year.

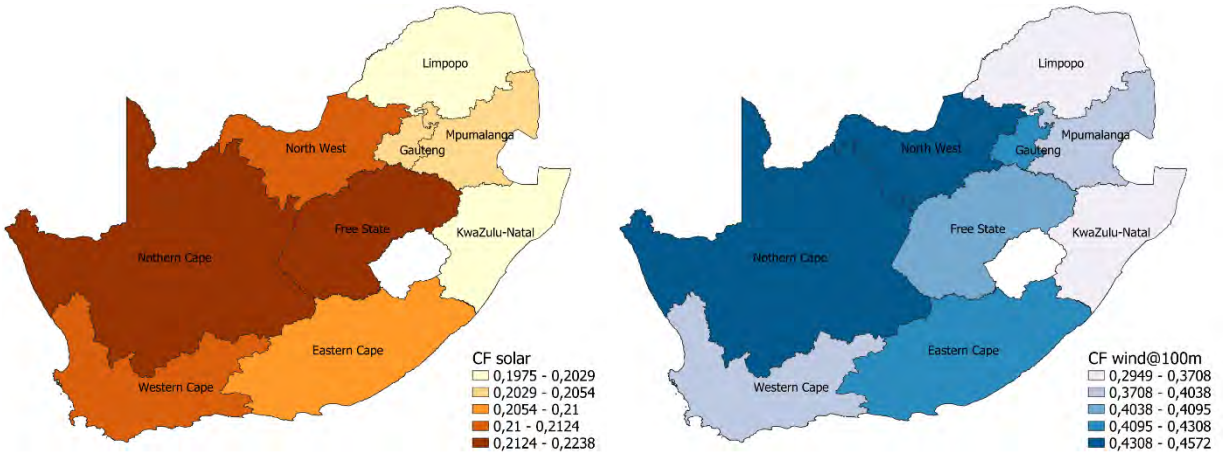
Outcomes - Step 2

The results confirm that for solar, its large potential translates into a large exploitability in almost all the Admissible areas of the country, ranging from 1700 kWh/kWp to 2000 kWh/kWp (Ⓢ 2000-2500 kWh/kWp). On the contrary, the amplitude of the energy yield range for wind is very large [e.g., 2000-5500 kWh/kWp (Ⓢ 1400-5000 kWh/kWp)], confirming the variability of wind resource exploitability on the national territory. Also, another interesting outcome is that the range of energy yield becomes larger at higher wind speeds, indicating that the distribution of wind speed during the year that is more variable in areas with stronger winds.

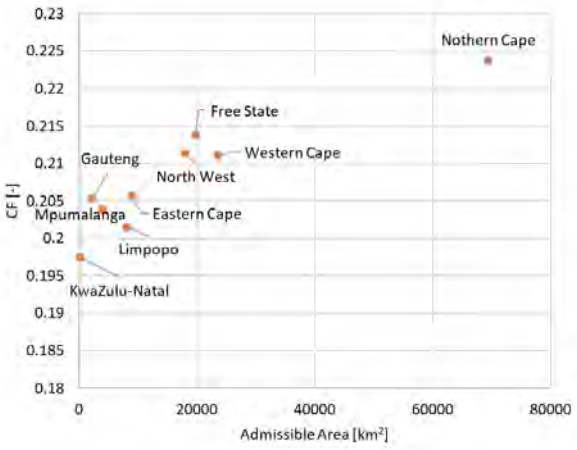


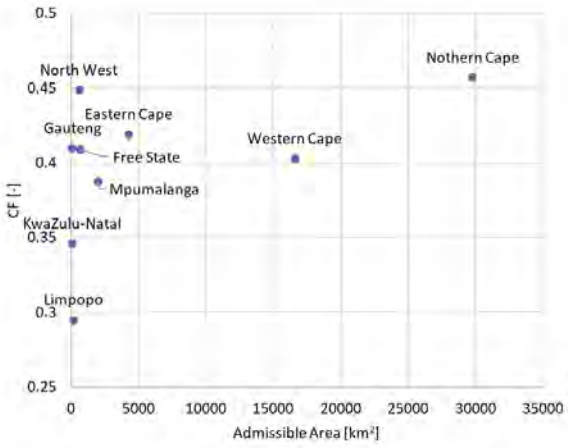
Step 3: Analysis of V-RES Availability

This step builds upon the quantitative results of the previous Step 1 and Step 2, to provide an overview and analytical discussion of the integrated V-RES potential and availability disaggregated by South African Provinces. A geographical representation of the absolute potential of V-RES in the South African Provinces is reported in figures below.



Since V-RES exploitability is subject to land restrictions, the two figures above should be read in conjunction with a representation of the Admissible areas, in order to properly assess the actual potential of V-RES in one Province respect to another. This is done through the next two figures that plot the solar and wind CFs with respect to the available Admissible areas by Province.





Outcomes (1/3) - Step 3

At glance, it can be concluded that from a generation perspective, the two most attractive Provinces for V-RES installations (both wind and solar) are Northern Cape and Western Cape, followed by Free State (mainly solar), North West (mainly solar), Eastern Cape (both wind and solar), and Limpopo (mainly solar).

To provide the reader with a more detailed analysis, an analysis for each Province is provided, with the following information:

- Table with summary indicators on the Admissible area for exploiting V-RES.
- Pie chart showing the share of V-RES types (PV, wind, or both) that could be installed in the Admissible areas.
- CF maps disaggregated by district municipalities for wind and solar PV.
- Volatility indicators for the wind resource:
    1. A raster map showing, for each province, the geographical distribution of the standard deviation of the wind velocity in the territory.
    2. A histogram with the probability density function of the standard deviation
- Volatility indicators for the solar PV resource: since the only available data are the average monthly CFs derived from the Global Solar Atlas from ESMAP, the volatility indicators are represented in a graph showing the monthly CFs along the year.

Outcomes (2/3) - Step 3

Eastern Cape, Western Cape and Northern Cape are the Provinces where the annual variability of wind resource reaches the highest values in some areas. North West, Free State, Gauteng, Limpopo are Provinces with the lowest average variability during the year of wind resource. Also, Eastern Cape, Mpumalanga, Northern Cape, Western Cape are Provinces with homogeneous values of wind speed standard deviation across the whole territory (i.e., similar annual variability of wind resource). On the contrary, North West, Free State, and Gauteng presents a degree annual variability that changes considerably based on the location.

KwaZulu Natal is the province with the most constant pattern of solar radiation in the year, while Eastern Cape, Northern Cape, and Western Cape are the Provinces with the highest seasonal variability of solar radiation.

Also, an energy-based case-study is reported to assess the benefits of PV-Wind integration at local level, namely at Komsberg substation with a representative 1 MW-peak load profile.

Outcomes (3/3) - Step 3

From the case-study, it is found that:

- The integration of Wind and PV minimizes the power production variability during the year, reaching its minimum with a 50:50 integration.
- Integrating VRES allows to have a flatter production during most days of the year, with smoother hourly variations.
- VRES integration is also beneficial to match the hourly energy production and consumption. The optimal integrated capacity that minimizes both the yearly overproduction and the unserved load is achieved by a capacity mix composed by PV (45%) and Wind (55%).

Step 4: Calculation of V-RES KPIs

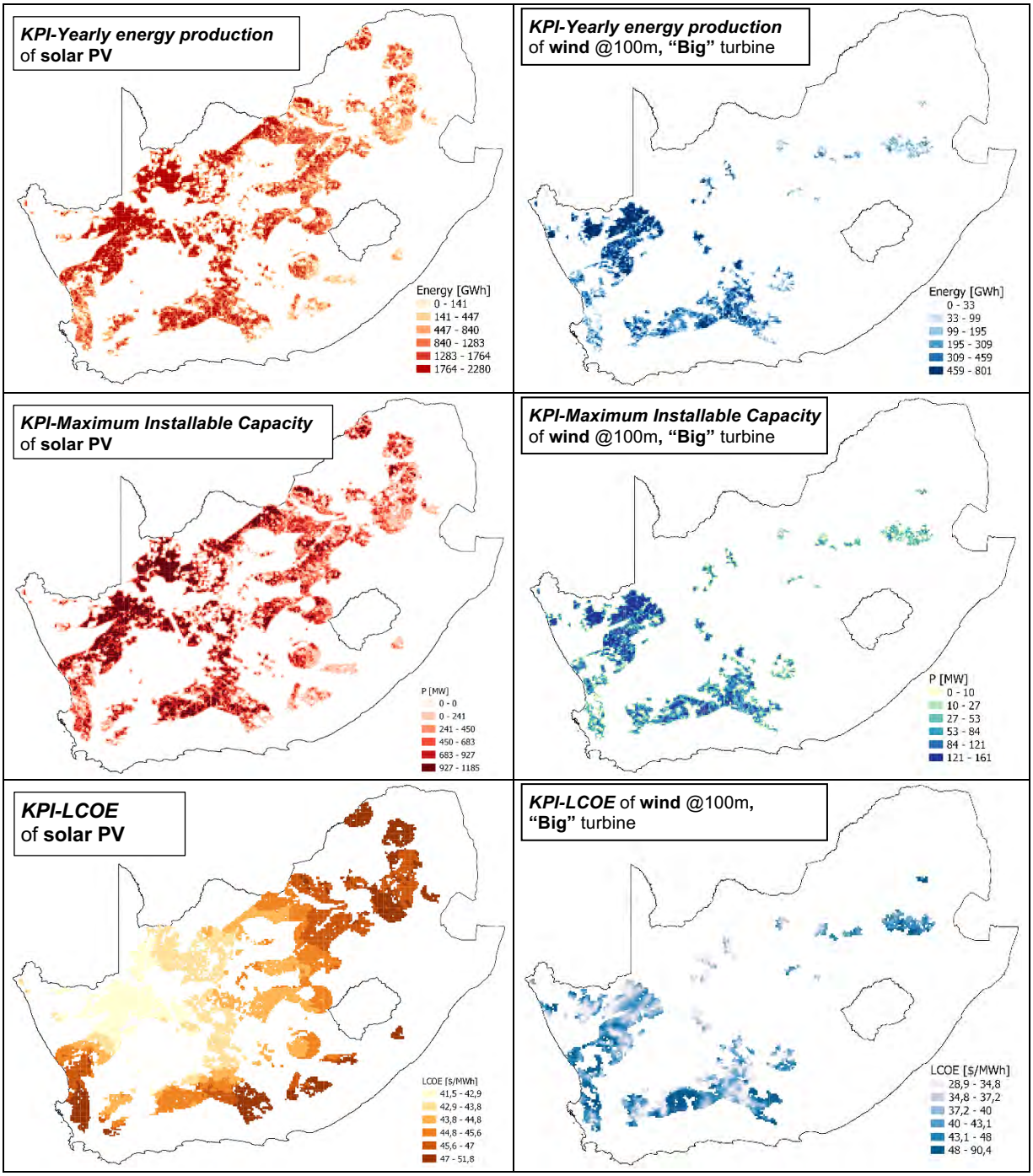
The goal of this step is to determine the KPIs to evaluate the optimal integration of V-RES in the areas where both wind and solar resources could be potentially exploited, and, in case of wind, evaluate the optimal technology. The KPIs are meant to assess the following aspects:

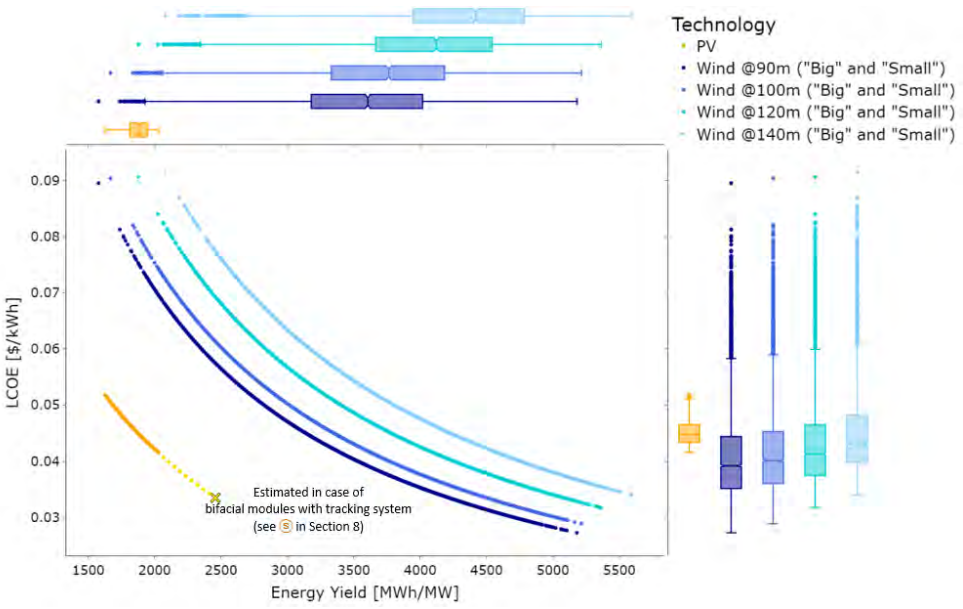
1. Maximum capacity installable of wind and solar plants, namely "*KPI-Maximum Installable Capacity*".
2. Maximum energy producible, namely "*KPI-Yearly energy production".*
3. Cost of energy, namely "*KPI-LCOE".*

Based on a combination of techno-economic assumptions useful to determine the performance of solar and wind power plants, and geospatial data derived in the previous Steps, the three KPIs have been calculated for each 5 km x 5 km pixel (called "Elementary Unit"), for both solar PV and wind. For wind, given the high variability of models and brands available on the market, 4 different reference turbines are considered:

1) IEC Class III turbine, with relatively "Small" power (4.7 MW, 155 m diameter).
2) IEC Class I-II turbine, with relatively "Small" power (5 MW, 145 m diameter).
3) IEC Class III turbine, with relatively "Big" power (6.6 MW, 170 m diameter).
4) IEC Class I-II turbine, with relatively "Big" power (6.6 MW, 155 m diameter).

Figures below reports the results for solar PV and for a "Big" wind @100m hub-height and a comparison of LCOE values between the technologies.

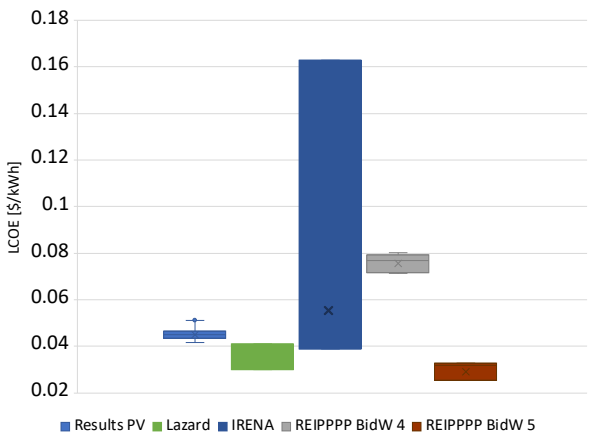

KPI-Yearly energy production of solar PV
Energy [GWh]
0 - 141
141 - 447
447 - 840
840 - 1283
1283 - 1764
1764 - 2280
KPI-Yearly energy production of wind @100m, "Big" turbine
Energy [GWh]
0 - 33
33 - 99
99 - 195
195 - 309
309 - 459
459 - 801
KPI-Maximum Installable Capacity of solar PV
P [MW]
0 - 0
0 - 241
241 - 450
450 - 683
683 - 927
927 - 1185
KPI-Maximum Installable Capacity of wind @100m, "Big" turbine
P [MW]
0 - 10
10 - 27
27 - 53
53 - 84
84 - 121
121 - 161
KPI-LCOE of solar PV
LCOE [$/MWh]
41,5 - 42,9
42,9 - 43,8
43,8 - 44,8
44,8 - 45,6
45,6 - 47
47 - 51,8
KPI-LCOE of wind @100m, "Big" turbine
LCOE [$/MWh]
28,9 - 34,8
34,8 - 37,2
37,2 - 40
40 - 43,1
43,1 - 48
48 - 90,4

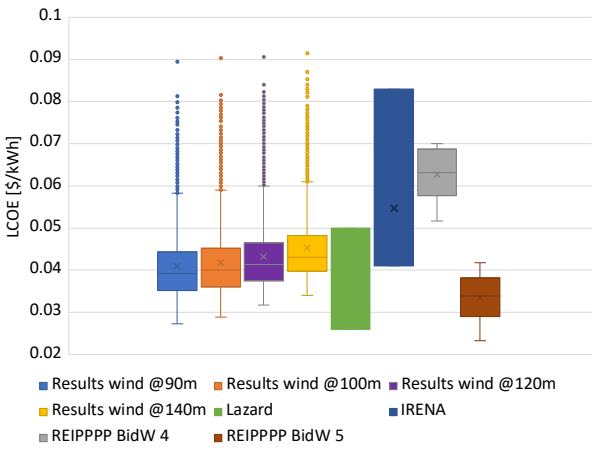


Outcomes (1/2) - Step 4

Focusing on the cost electricity reported in the previous figure, since solar PV plants have a more homogeneous energy yield across the country, this leads to less variable solar LCOE values when compared to wind plants: LCOE ranges from around 50 $/kWh to around 40 $/kWh (Ⓢ 33 $/kWh to around 41 $/kWh) for PV plants against a range of 90 $/kWh to 30 $/kWh (Ⓢ 200 $/kWh to 21 $/kWh) in the case of wind plants. In case of wind, the LCOE increases with the hub height of the turbines, showing that the higher energy production exploitable at higher altitudes does not necessary compensate the higher costs faced for the installation of taller turbines.

To contextualize the obtained results on LCOE, they are compared with LCOE values taken from literature (Lazard and IRENA) and with the bid prices of the South African Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) (see Figure 29 and Figure 30).





Outcomes (2/2) - Step 4

LCOE values obtained in the analysis are positioned in the higher range of LCOE values from Lazard and in the lower band of values from IRENA, hence in line with literature values. Concerning the comparison with the REIPPPP prices, the LCOE for both wind and solar are lower than the BidW4 (2014) results, but higher than the latest BidW5 (2021), whose results are almost halved with respect to 2014. The reasons behind the misalignment between simulation results and BidW5 prices may be manifold, such as the not matching boundary conditions, while the full contract details are not available, meaning there could be additional payments or strategic business opportunities to raise revenue beyond the headline PPA price.

Step 5: Optimization of V-RES Integration

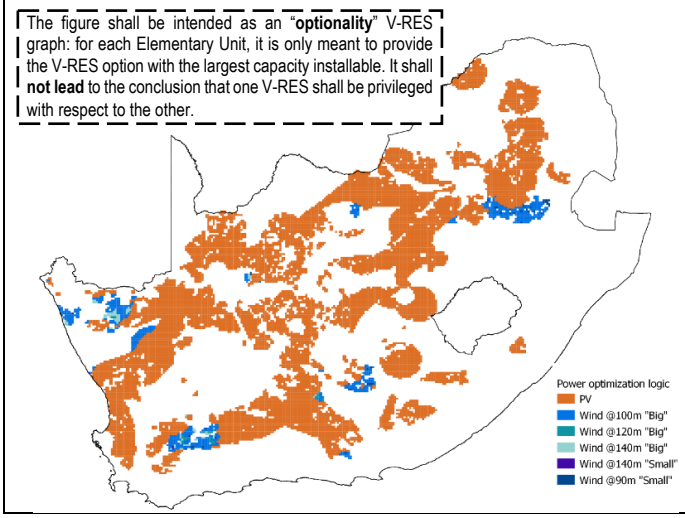
Most of the Admissible areas represent zones where both solar and wind can be potentially exploited. So far, the analysis kept separate the solar and wind Atlases, to analyse the potential of each V-RES independently. The goal of Step 5 of the procedure is to provide a single integrated solar and wind Atlas, by identifying the optimal integrated mix of V-RES for each Elementary Unit (5x5 km^2). To optimally allocate the two V-RES in the Elementary Units where both solar and wind may be installed, three (3) potential different alternative logics have been considered:

- *Power optimization*: in this case, in each Elementary Unit of the overlapped Atlases, the V-RES with the highest *KPI-Maximum Installable Capacity* [MW] is selected.
- *Energy optimization*: in this case, in each Elementary Unit of the overlapped Atlases, the V-RES with highest *KPI-Yearly energy production* [MWh/year] is selected.
- *Economic optimization*: in this case, in each Elementary Unit of the overlapped Atlases, the wind turbine with lowest LCOE (chosen among the different heights and IEC Class) is compared against solar, and the V-RES with lowest *KPI-LCOE* [$/MWh] is selected.

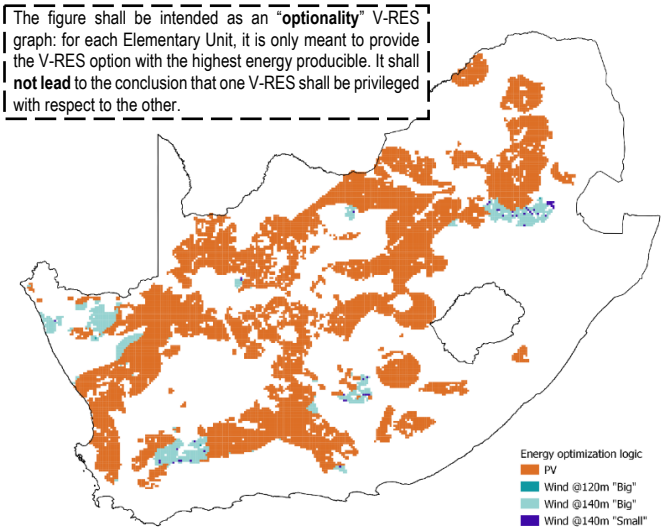
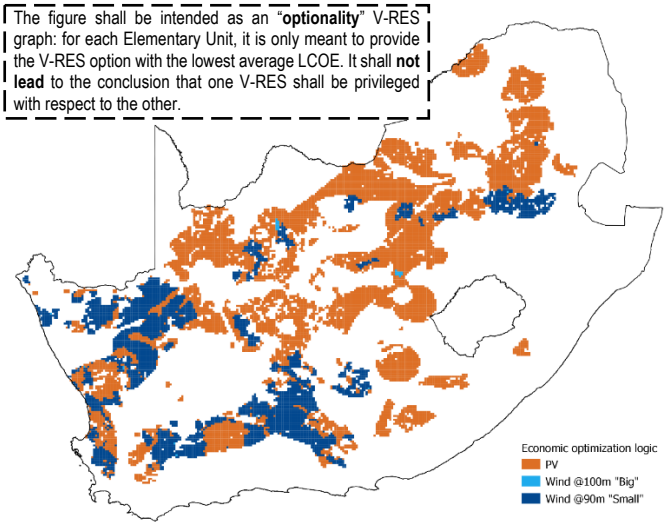
The results for each optimization logic are shown in maps and resuming tables that report the global values of the three KPIs on the whole territory for solar, wind, and "total" after the optimization performed for each Elementary Unit:

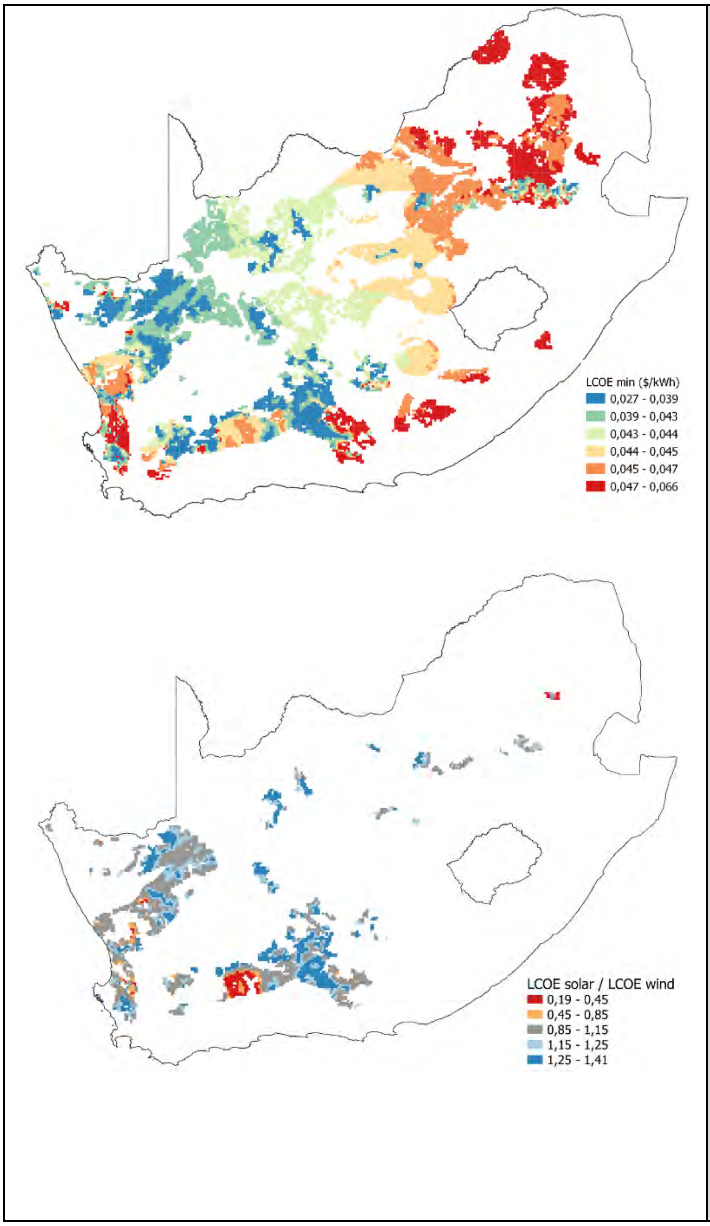
Outcomes – Step 5

OPTIMIZATION LOGIC: *Maximization of KPI-Maximum Installable Capacity*



- Since PV plants occupy less area per MW with respect to wind plants (2.4 ha/MW (Ⓢ 1.6 ha/MW) against around 20 ha/MW, as per hypothesis introduced in Step 2), PV results to be the optimized solution with a maximum capacity installable of 6.4 TW (Ⓢ 9.6 TW) and yearly energy producible of 12000 TWh (Ⓢ 22000 TWh).
- Among the different types of wind turbines, "Big" turbines have a lower land occupation and hence preferred in most of the cases. The optimized hub height is 100 m, which is the one that allows to have the

	turbines with the highest IEC Class (I and II) and lower land occupation per MW. • The power optimization criterion does not lead to an optimal allocation from a cost minimization-perspective. In fact, the average LCOE of the solar-covered areas is around 12% higher (Ⓢ 17% lower) with respect to the wind-covered areas, which leads to a global average LCOE that is around 44.4 $/MWh (Ⓢ 35.8 $/MWh).
OPTIMIZATION LOGIC: *Maximization of KPI-Maximum Energy Production*	
The figure shall be intended as an "**optionality**" V-RES graph: for each Elementary Unit, it is only meant to provide the V-RES option with the highest energy producible. It shall **not lead** to the conclusion that one V-RES shall be privileged with respect to the other. 	• Also with this logic the PV prevails over wind in all the common Elementary Units, with a maximum capacity installable of 6.4 TW (Ⓢ 9.6 TW) and yearly energy producible of 12 000 TWh (Ⓢ 22000 TWh). This is a direct consequence of the fact that the higher Capacity Factor (CF) of wind in the Elementary Units is not enough to offset the higher KPI-Maximum Installable Capacity of solar in the same Elementary Unit. • The prevailing chosen types of wind turbines is the "Big" turbine at 140m hub height, since the CF is higher at higher heights. • The selection of taller wind turbines leads to an increase of the LCOE of wind plants with respect to the power optimization logic (from 39.6 $/MWh to 42.5 $/MWh) (Ⓢ from 42.9 $/MWh to 44.4 $/MWh).
OPTIMIZATION LOGIC: *Minimization of KPI-LCOE*	
The figure shall be intended as an "**optionality**" V-RES graph: for each Elementary Unit, it is only meant to provide the V-RES option with the lowest average LCOE. It shall **not lead** to the conclusion that one V-RES shall be privileged with respect to the other. 	• In the Elementary Units where both solar and wind could be exploited, it is wind that has the lowest LCOE in most (Ⓢ some), of the cases, so the global max capacity installable of wind increases with respect to the previous cases up to 204 GW (Ⓢ 78 GW), a yearly energy producible of 783 TWh (Ⓢ 266 TWh), and an average LCOE of 36.9 $/MWh (Ⓢ 37.4 $/MWh). Solar PV still dominates with a maximum capacity installable of 4.5 TW (Ⓢ 9.0 TW), a yearly energy producible of 8 500 TWh (Ⓢ 21 000 TWh), and an average LCOE of 44.8 $/MWh (Ⓢ 35.7 $/MWh). • The total V-RES Max capacity installable and the Max yearly energy producible are lower than the results obtained with the previous two logics. This is a consequence



of the fact that the power density of wind installations is lower than solar (i.e., they require more available land per unit of power output), and so a higher number of Elementary Units with wind installations leads to a decrease of global Max capacity installable and Max yearly energy producible.

- The cost of electricity is slightly cheaper than in the previous two logics: the total weighted average LCOE of the country equals 44.1 $/MWh (Ⓢ 35.7 $/MWh).
- The LCOE in the country ranges from a minimum of 27 $/MWh (Ⓢ 26 $/MWh) in the North Cape and Western Cape provinces to a maximum of 66 $/MWh (Ⓢ 85 $/MWh) in the north-eastern part of the country.
- For wind, "Small"-types turbines @ 90 m of hub-height represent the optimized solution almost everywhere, given the lower LCOE at lower hub heights.
- Finally, the figures above shall not necessarily lead to a conclusion that one source shall be privileged to the other in a given Elementary Unit. To confirm this, the last figure aside reports the ratio between the solar LCOE and the wind LCOE in the areas where both wind and solar can be installed, colouring in grey the areas where the two LCOEs vary of less than ± 15%. As displayed, most of the territory falls within this grey band, meaning that the affordability of one source with respect the other is very similar.

Step 6: V-RES Localisation and Power System Implications

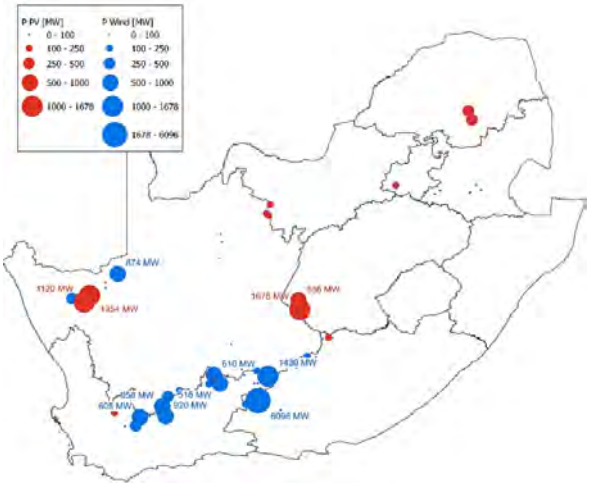
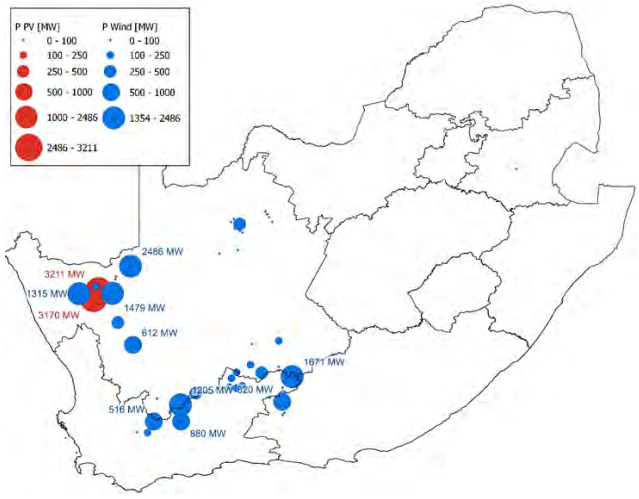
The Step 6 aims at deriving insights on the most promising locations for the installation of new V-RES plants and assessing the implication of their massive integration on the South African power system from an economic and a grid development perspective. This Step is approached through two analyses with the following specific goals:

1. **Part 1:** Evaluating the most promising locations for the installation of new wind and PV power plants, according to an economic merit-order allocation, refined with considerations on grid proximity.
2. **Part 2:** Evaluating the expected impact of the LCOE on the V-RES and total energy component of the current electricity tariff in South Africa.

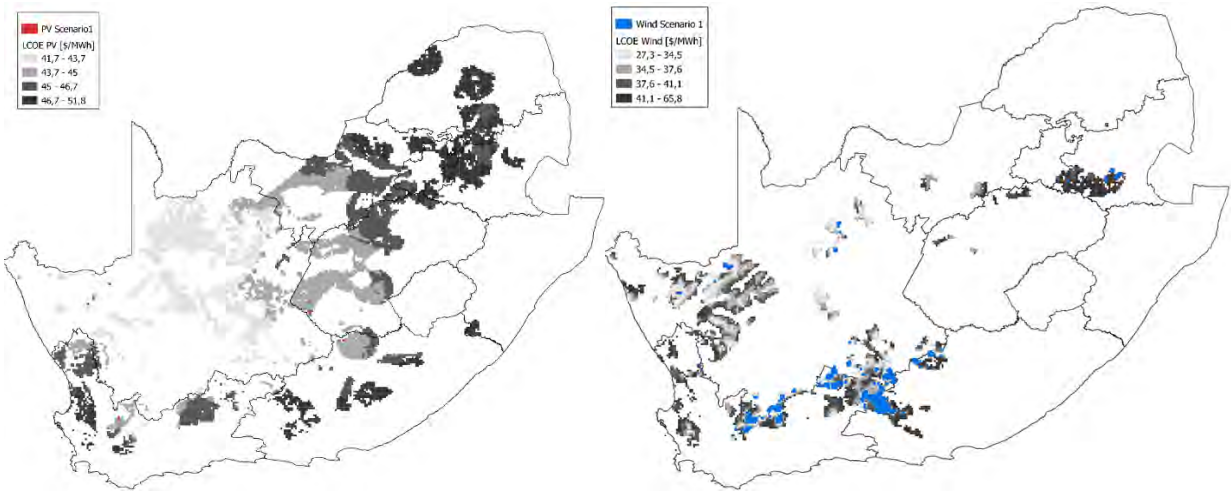
The data used as input for this last Step of the study are the results of the previous steps and the information on the latest *Generation plan from IRP and TDP2021* (covering the 2022-2031 period), the

latest I*PP plants*, the geospatial data related of the existing and planned transmission network of South Africa, and estimations on the current cost of electricity supply for Eskom. The latest *TDP2022* (covering the 2023-2032 period), published concurrently to the finalization of this study, substantially increases the target quantities of V-RES in 2031 in South Africa and it is not expected to impact on the hypotheses and outcomes of this study based on the TDP2021.

Part 1 has been tackled by allocating the expected new installations of V-RES in South Africa (around 20 GW) according to the economic-merit order based on the lowest LCOE with (Scenario 1) and without (Scenario 2) respecting the Province subdivision provided in the IRP.

Outcomes (1/6) - Step 6	
Scenario 1 (<u>with</u> IRP Provinces' allocation)	
	In terms of areas selection, Western Cape is the Province that is expected to allocate the largest area for V-RES localization, mainly wind farms, and it turns out to be the Province with the highest V-RES capacity penetration. Eastern Cape follows, with almost 6 GW (Ⓢ 6 GW) of wind plants localized in the north of the Province at an average LCOE of 33.2 $/MWh (Ⓢ 32.0 $/MWh). The expected capacity of solar PV is almost equally split between Free State (around 2.2 GW at 44 $/MWh) (Ⓢ 2.2 GW at Ⓢ35 $/MWh) and Northern Cape (around 2.5 GW at 41.7 $/MWh) (Ⓢ 2.5 GW at Ⓢ 33 $/MWh), which in turns is expected to host also 2 GW of wind farm at 29.6 $/MWh (Ⓢ 2 GW at Ⓢ 29.7 $/MWh).
Scenario 2 (<u>without</u> IRP Provinces' allocation)	
	The relaxation of the IRP Province-boundary constraint leads to the conclusion that the least-cost localization of V-RES converges towards the areas with the highest V-RES potential (and lowest LCOE), that are mainly concentrated in Northern Cape (the total capacity of Solar PV, 6.5 GW, together with around 62% of the total capacity of wind, 9.2 GW out of 14.7 GW). Nevertheless, the effective benefits of Scenario 2 with respect to Scenario 1 in terms of Max yearly energy producible [TWh] (around 4% higher for both V-RES) and Average LCOE [$/MWh] (around 4% lower) are negligible.

The similar LCOE results from the two scenarios finds its explanation in the figure below, where it clearly emerges that the selected Elementary Units for localizing solar in Scenario 1 are surrounded by large areas with the same/similar LCOE values. Also, wind has some degree of freedom, but not so huge as the one of solar PV, since the selected Elementary Units for localizing wind in Scenario 1 in each Province already cover the areas with the lowest LCOE values.

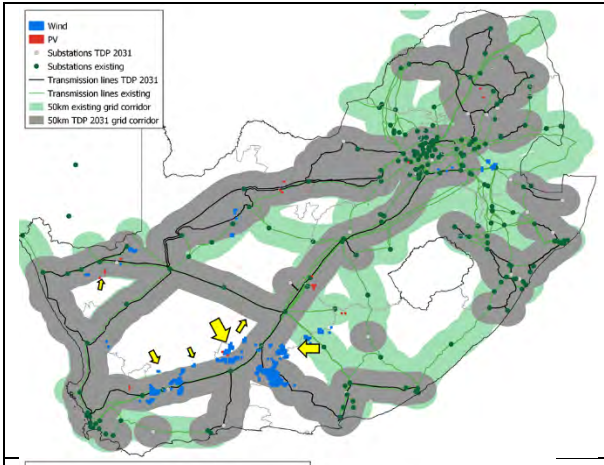


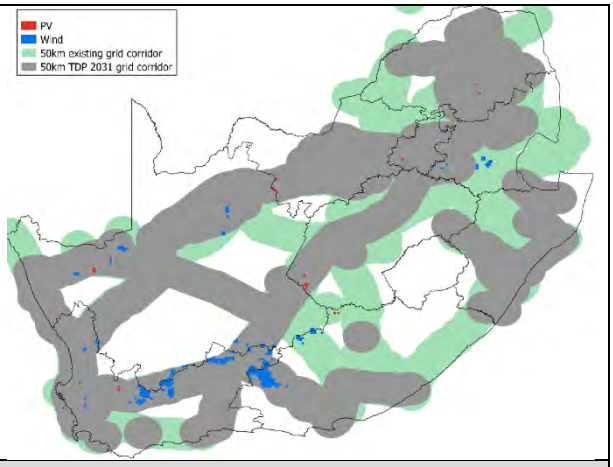
Outcomes (2/6) - Step 6

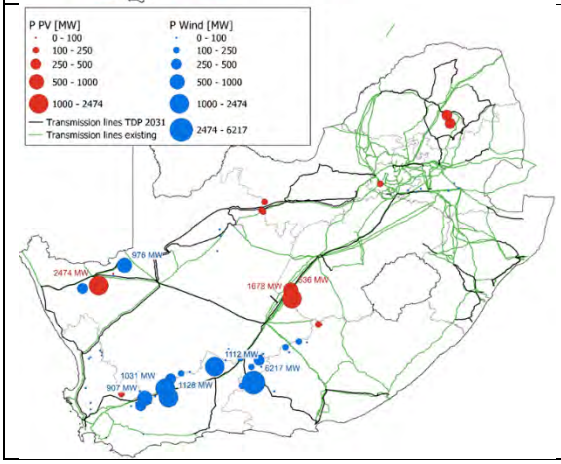
In general, we can conclude that there is room for allocating V-RES in low-cost areas, while also considering the current grid congestion challenges that the South African power system is experiencing. For example, in case a more disaggregate V-RES distribution within or among provinces could avoid worsen or even improve the power system condition, areas with slightly higher LCOE could be evaluated, without greatly impacting the final costs.

The previous considerations shall be read net of grid implications. That is the reason why V-RES capacity has been re-allocated within a 50 km-corridor from the existing and planned transmission grid following the least-cost driven path.

Outcomes (3/6) – Step 6

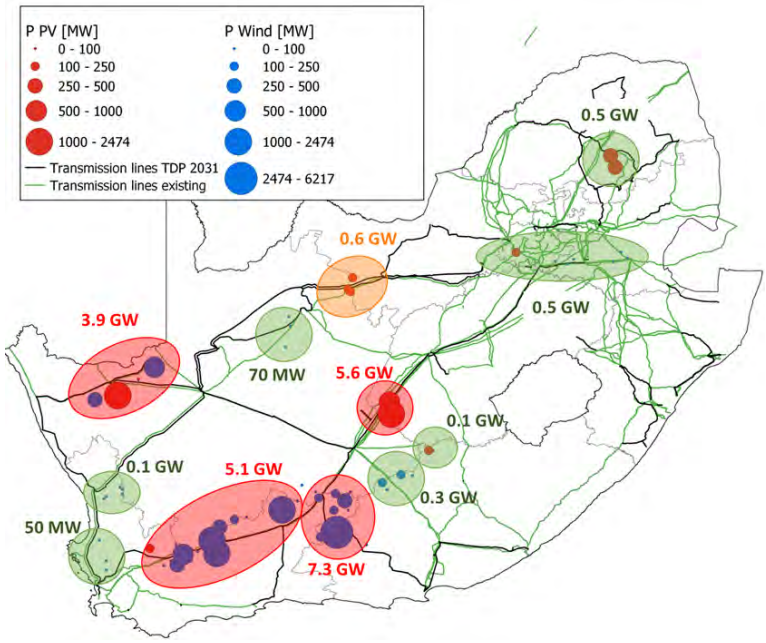






With respect to the results of the Scenario 1 without grid proximity considerations, the re-allocation within each Province leads to almost negligible differences in terms of Max yearly energy producible [TWh] (around 0% and 1% lower for solar and wind, respectively) and Average LCOE [$/MWh] (around 0% and 1% higher for solar and wind, respectively), confirming that guiding V-RES localization in the least-cost Elementary Units within a 50 km-corridor surrounding the existing and planned grid is still a near-optimal allocation that minimizes the average LCOE.

The above results allow to provide preliminary insights on the possible areas where the grid (existing and planned) may deserve more attention through detailed power system study to assess the impact of V-RES installation. As preliminary step, the figure below reports the re-allocated (<50 km) capacities of localized V-RES grouped in three different clusters: *Cluster 1 (red), expected high impact, Cluster 2 (orange), expected medium impact*, *Cluster 3 (green), expected low impact)*. The level of impact has been estimated based on whether the new plants are expected to connect to the existing portions of the grid/substations or the new planned ones and based on the estimated level of congestion in the different Provinces, according to the Generation Connection Capacity Assessment (GCCA) 2024, which gives information on generation connection capacity within the network readily accessible, incorporating all the bid windows up to round BidW5.

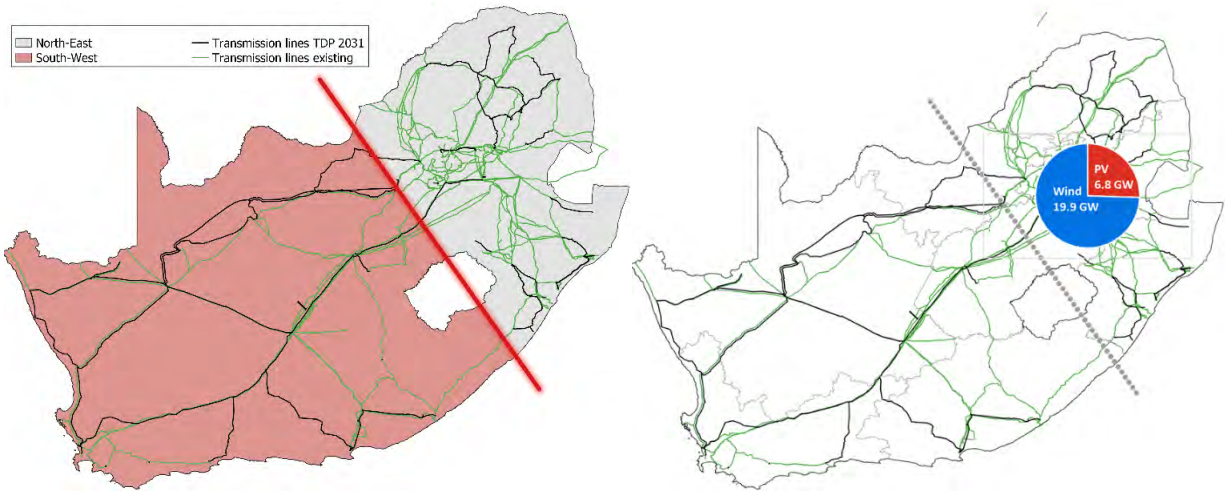


Outcomes (4/6) - Step 6

1) *Cluster 1 (red), expected high impact:* it includes four (4) groups of V-RES installations, for which a proper grid impact assessment is suggested:
    a. The 3.9 GW group in the north-west area of Northern Cape, composed by around 2.4 GW of solar PV and 1.5 GW of wind. In the whole Northern Cape, 0 GW of connection capacity is readily accessible as per GCCA, but relevant grid reinforcements are expected as per TDP 231.
    b. The 5.1 GW group (mainly wind) on the line at the border between Northern Cape and Western Cape, and the 7.3 GW group (all wind) on the line at the border between Western Cape and Eastern Cape. According to the GCCA, the connection capacity readily accessible in the two Capes is not sufficient to host the new expected connections, but relevant grid reinforcements are expected as per TDP 231.
    c. The 5.6 GW group (only solar) on the corridor in Free State. According to the GCCA, the connection capacity readily accessible in the Province is higher than 4 GW but is not sufficient to host the new expected connections. Again, relevant grid reinforcements are expected as per TDP 231.
2) *Cluster 2 (orange), expected medium impact:* it includes three (3) groups of V-RES installations:
    a. The 0.6 GW group (solar) on the corridor at the border between Northern Cape and North West, which may be affected by the null connection capacity readily accessible, as per GCCA, in Northern Cape, but a relevant double-lines reinforcement is expected as per TDP 231.
3) *Cluster 3 (green), expected low impact:* all the remaining groups where the expected connection capacity is well below the readily accessible connection capacity in the Provinces, as per GCCA, and grid reinforcement are expected as per TDP 2031.

A further analysis was performed to evaluate the differential cost of installing all the V-RES plants in the North-Eastern part of the country, in contrast with the optimal solutions identified in the previous stage that favour the V-RES localisation in the Western part of the country. The goal is to identify an optimal trade-off between installing V-RES plants in areas with high availability of V-RES but far from the load

centres and that require a massive investment in grid extension and reinforcement (West side), and installing plants in areas (North-East side) with higher LCOE but closer to the load centres and therefore that require less investments on grid reinforcement.



Outcomes (5/6) - Step 6

The results indicate a differential cost over a horizon of 30 years of around 7.5 billion USD (Ⓢ 10.4 billion USD). Considering this value as a proxy for the cost-opportunity to invest in transmission grid expansion of the West-East corridor, it suggests that as long as the cost for reinforcing the infrastructure in the South-West area and the interconnection towards the load centres is significantly below this number, it may be worth to prioritize the Western areas with lowest LCOE for installing V-RES plants. This 7.5 billion-figure (Ⓢ 10.4 billion USD) should be intended as the order of magnitude of the actual cost-opportunity to be further adopted in eventual strategic planning decisions. In fact, deeper cost-benefit and financial analyses, which are out of the scope of this study, should be taken into consideration in order to include also the factors that may have and incremental or decremental impact of that figure, such as the needs for grid reinforcements for the West-East corridor even in the "reallocated" scenario since a large capacity may still need to be allocated in the West part due to insufficient available land in the North-East area.

Concerning Part 2 on electricity tariff, time-series of data on the current electricity generation mix in South Africa and the variable electricity supply cost for Eskom for the various generation sources are analysed to critically discuss the observed trends in variable generation costs in the recent years. From the analysis, it emerges that the increase of the energy component MEGAFlex tariff of the last few years can be partially linked to the increased costs of energy procurement from V-RES IPPs and the increase in coal cost.

In terms of impact of the results obtained in the previous Part of Step 6 on the cost of electricity, the analysis considered the cost of the new VREs plants from REIPPPP BidWin5 and the ones calculated after the optimal geospatial allocation performed in Scenario 1 (with IRP Provinces' allocation) in Part 1 of this Step 6.

Outcomes (6/6) - Step 6

The commissioning of the new expected capacity may lead to a substantial decrease of the total weighted average supply costs from renewable IPPs for Eskom: from the 146.4 $/MWh of 2021 (based

on the latest available data from the Eskom Integrated Report 2021) to around 50 $/MWh (Ⓢ 50 $/MWh) in 2031.

Moreover, based on the results of optimal V-RES generation obtained in this study, it is possible to state that a gradual replacement of coal generation by V-RES generation will decrease the cost of supply. The variable electricity supply cost for Eskom from coal for 2031 estimated by CESI is 79 $/MWh, significatively higher that the LCOE for wind and solar PV, with the result that exploiting V-RES generation for substituting (part of) coal generation by 2031 will lead to a decrease in the in the supply costs for Eskom. This should, other things being equal, bring about a reduction (or at least a stabilization) of the energy component of the MEGAFlex tariff.

1. INTRODUCTION

South Africa has a well-developed electricity network and one of the highest rates of electricity access in sub-Saharan Africa. Electricity generation in South Africa is reliant on coal (over 70% of the energy consumption), but efforts are ongoing to diversify the energy mix, as the coal-fired fleet is ageing, and new projects will not fully compensate for the decline of the existing fleet. The government is focusing on diversifying the power mix by introducing natural gas and renewables.

The total generation capacity installed in 2021 was 56 GW (to cover a peak load demand of around 35 GW), of which 12% composed by renewables and 88% by conventional generation. The National Development Plan 2031 envisages a decommission of 35 GW (out of 42 GW currently operating) of coal-fired power capacity and supply at least 20 GW of the additional 29 GW of electricity needed by 2031 from renewables and natural gas.

According to the Integrated Resource Plan (IRP) 2010–2030 (2019 edition) 6,000 MW of new solar PV capacity and 14,400 MW of new wind power capacity will be commissioned by 2030. Such amount of variable renewable generation needs to be integrated into the power system implementing adequate actions aimed at assuring the system security and reliability.

With this Project, CESI, as an active member of RES4Africa foundation, aims at supporting RES4Africa and Eskom in this transition phase towards a decarbonized power sector in South Africa.

The General Objective of this activity is therefore to contribute to meet the IRP targets by addressing the integration of non-programmable renewable energy sources (V-RES), namely solar and wind, into the South African national electricity system (NES).

The Specific Objective of this activity is to perform a geospatial analysis aimed at exploring the **value of V-RES** (i.e., solar and wind) in South Africa. More in detail, the assessment of V-RES value concerns the following aspects:

- **Potential:** expected specific Yield [kWh/kWp] of V-RES with high spatial resolution.
- **Exploitability**: candidate V-RES generation is proposed for each spatial element, to identify the optimal maximum capacity and production.
- **Economics**: calculation of Levelized Cost of Energy (LCOE) for V-RES with high spatial resolution.
- **Viability**: investigation of locations of high-RE potential considering the expected yield of the RE resources, giving priority to the areas with the lowest cost of electricity, higher production, and proximity to the existing and planned grid.
- **Impact**: evaluation of the grid implications of V-RES exploitability in the current and expected evolution of the South African power system, as well as on the current electricity tariff.

Any quantitative consideration on the impact of the results on the operation of the South African Transmission Grid are excluded from the analysis, since it would require appropriate network studies that are out of the scope of this study, as agreed upon with RES4Africa first, and also shared with Eskom.

2. SCOPE AND RATIONALE OF THE REPORT

This deliverable constitutes the results of the "Integration of Non-Programmable Renewable Energy in the National Electric System of South Africa" project. The project is framed within the assistance that CESI S.p.A. is providing to RES4Africa, as one of its active member and technical partner.

This Report provides the assumptions, steps, results, and outcomes of the whole Project, to provide the relevant stakeholders all the necessary elements to identify the actual value of V-RES (i.e., solar and wind) in South Africa in terms of Potential, Exploitability, Economics, Viability, Impact criteria, as reported in the previous Section.

The Report envisages to benefit especially (not exhaustive list):

- *RES4Africa Foundation*: as facilitator of RES-oriented actions and polices in the South African power system, to continue providing efficient support for an effective energy transition in South Africa.
- *ESKOM*: as system operator and developer of the South African Grid, to steer and guide the operation and planning endeavours in a way that they go hand-in-hand with the expected localisation of RES penetration in the Country.
- *IPP Office (Department of Mineral Resources and Energy)*: as entity in charge of enabling the increase in RES capacity to be procured under the Renewable Energy IPP Procurement Programme.
- *RES Developers*: as investors in RES plants and future Users of the South African Grid, to support the identification of the most profitable locations for RES development.

As introduced in the Inception Report (Task 1) of the Project, the study has been performed through a six (6) steps-wise methodology, which represents the core of this Report and constitutes its structure:

- Section STEP 1: GEOSPATIAL DATA COLLECTION AND CREATION OF SOLAR AND WIND ATLASES: it analyses the renewable resources potential in South Africa in the areas available for V-RES installations, excluding the not admissible zones, with high geospatial resolution.
- Section STEP 2: IDENTIFICATION OF RESOURCES TECHNICAL POTENTIAL (CAPACITY FACTOR ASSESSMENT): it evaluates the technical potential, in terms of capacity factor (CF) and annual specific energy yield per unit of power capacity installed [kWh/kWp] of solar and wind resources, of the whole South Africa with high geospatial resolution.
- Section STEP 3: ANALYSIS OF V-RES AVAILABILITY: it provides an analytical, critical, and global discussion of the integrated V-RES potential and availability in the country, based on the punctual results derived in the previous two Sections.
- Section STEP 4: CALCULATION OF V-RES KPIS: it introduces, discusses, and calculates the Key Performance Indicators (KPIs) that allow to estimate the maximum capacity installable of wind and solar plants, the maximum energy producible, and the levelized cost of energy.
- Section STEP 5: OPTIMIZATION OF V-RES INTEGRATION: it identifies the optimal integrated mix of V-RES with high spatial resolution by considering three different alternative logics for the integration of solar and wind resources: *Power optimization*, *Energy optimization, Economic optimization.*
- Section STEP 6: V-RES LOCALISATION AND POWER SYSTEM IMPLICATIONS: it assesses the potential implications of the results on the power systems in terms of grid development and impact of the tariff. Scenarios are built at the light of the latest Transmission Development Plan

(TDP) available, which provide the expected and planned penetration of V-RES in South Africa and its allocation in the different Provinces.

3. STEP 1: GEOSPATIAL DATA COLLECTION AND CREATION OF SOLAR AND WIND ATLASES

3.1 Goal

The goal of the first step of the study is the creation of V-RES Atlases reporting the renewable resources potential in South Africa excluding the unfeasible zones, i.e., the areas where it would not be possible to deploy large scale V-RES based plants due to physical and regulatory constraints. This potential, which can be defined as a bounded theoretical potential, should be expressed in terms of useful indicators, representative of the amount of energy provided by the V-RES per unit surface area:

- For the solar resource, the Atlas will report indicators related to solar irradiation.
- For wind resource, the Atlas will report indicators related to the average wind speed that determines the energy extractable from wind turbines.

3.2 Procedure

The adopted procedure follows the steps described in detail in the following paragraphs aimed to collect the input data and process them in order to generate the desired output.

3.2.1 Input data collection

Starting from the data analysis reported in the Inception Report and following the discussion and the points agreed upon with RES4Africa and Eskom, the following data (and related indicators) have been used:

- *Global Horizontal Irradiation (GHI)*: it is the average yearly solar irradiation comprising both the diffuse and direct irradiance on a horizontal plane.
- *Global Tilted Irradiation (GTI)*: it is the average yearly solar irradiation comprising both the diffuse and direct irradiance on a plane inclined at the optimum tilt angle. This is the angle, that, at a specific location, maximises the amount of irradiation received during a year.
- *Average wind speed:* it is the yearly average emergent wind speed measured at different hub heights. For the study, data related to 50m, 100m and 150m above the ground have been retrieved.
- *Weibull wind scale parameter* (*A* coefficient): it is one of the two coefficients that characterise the Weibull distribution for wind. The *A* coefficient is proportional to the mean wind speed, and it also describes how the distribution is stretched, with lower values corresponding to a narrower distribution with higher peak. For the study, data related to 50m, 100m and 150m above the ground have been retrieved.
- *Weibull wind shape parameter* (*k* coefficient): it is the second one of the two coefficients that characterise the Weibull distribution for wind. It describes the shape of the wind probability distribution. Small value for k signifies very variable winds, while constant winds are characterized by a larger *K*. A value close to 3 approximates a normal distribution. For the study, data related to 50m, 100m and 150m above the ground have been retrieved.
- *Admissible areas:* Polygon vector layer containing the areas with solar development potential. It reports the areas with the solar irradiance and wind potential after environmental restrictions are considered. Those areas were identified in the Strategic Environmental Assessment (SEA) study of the Council for Scientific and Industrial Research (CSIR).

To better explain the meaning of the Weibull parameters, it is important to recall the Weibull distribution function. The probability density function $f(v)$ of the wind velocity can in fact be expressed by a Weibull distribution, dependent on the shape parameter k and the scale parameter A, introduce before, whose formula is the following:

$$f(v) = k/A \cdot \left(\frac{v}{A}\right)^{k-1} e^{-\left(\frac{v}{A}\right)^{k}}$$

Table 1 Data used for Step 1.

Data	Unit	Type	Data Provider	Temporal resolution	Spatial resolution
GHI	kWh/m^2/y	Raster	Global Solar Atlas [1]	Yearly	250x250 m^2
GTI	kWh/m^2/y	Raster	Global Solar Atlas [1]	Yearly	250x250 m^2
Wind speed	m/s	Raster	WASA [2]	Yearly	250x250 m^2
Weibull A	m/s	Raster	WASA [2]	Yearly	250x250 m^2
Weibull k	-	Raster	WASA [2]	Yearly	250x250 m^2
Admissible areas	-	Vector	Eskom data	-	-

3.2.2 Data processing

The raster files of the solar and wind resources have been intersected with the polygon vector file of the *Admissible areas*, to keep only the pixels covering the Admissible areas. All the pixels touching, even partially, the available areas, have been included in the output raster. In this way, the output shows the V-RES potential available in all the Admissible areas of South Africa. For each one of the five (5) solar and wind indicators (at heights of 50m, 100m and 150m) reported in the previous Section (GHI, GTI, Wind speed, A, k), the outputs are in the form of raster files with a resolution of 250 m x 250 m. An html interactive map showing the results for solar and wind resource at 100m height is also provided. The raster files have also been combined in a polygon vector file, showing graphically both the solar and wind resource in South Africa. The attributes associated to each polygon correspond to the solar irradiation (i.e., GHI, GTI), wind speed values and Weibull coefficients at different heights (i.e., wind speed@100m, wind speed@150m, A@50m, A@100m, A@150m, k@50m, k@100m, k@150m).

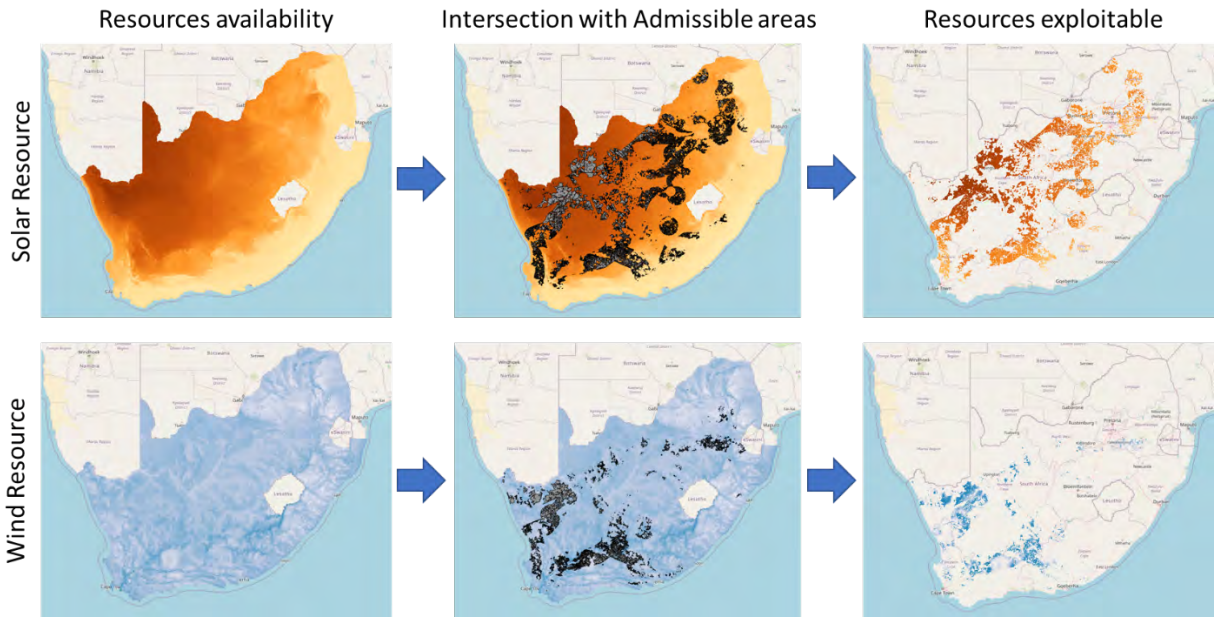


Figure 1 Procedure for processing geospatial V-RES data.

3.2.3 Output

The outputs of the Step 1 are delivered as follows:

1. *GHI Atlas*: one (1) raster file (.tiff format), with pixel size equal to around 250x250 m^2. Pixel values expressed in kWh/m^2/year.
2. *GTI Atlas*: one (1) raster file (.tiff format), with pixel size equal to around 250x250 m^2. Pixel values expressed in kWh/m^2/year.
3. *Wind Speed Atlas*: three (3) raster files (.tiff format), with pixel size equal to around 250x250 m^2. Pixel values expressed in m/s. Heights above ground: 50, 100, and 150m.
4. *Weibull A Atlas*: three (3) raster files (.tiff format), with pixel size equal to around 250x250 m^2. Pixel values expressed in m/s. Heights above ground: 50, 100 and 150m.
5. *Weibull k Atlas*: three (3) raster files (.tiff format), with pixel size equal to around 250x250 m^2. Pixel values are adimensional. Heights above ground: 50, 100 and 150m.
6. *Comprehensive Atlas*: one (1) polygon vector file, with polygons of 5x5 km^2 size. Attributes of each polygon are: GHI, GTI, wind speed@50m, wind speed@100m, wind speed@150m, A@50m, A@100m, A@150m, k@50m, k@100m, k@150m.
7. *Html map*: file composed of 4 interactive maps showing the value of GTI and wind speed@100m in the whole South Africa and in the Admissible areas.

3.3 Results and discussion

This Section aims at discussing the results of V-RES availability in South Africa.

The following maps report the screenshots from two of the Atlases in outputs: the GTI Atlas and the Wind Speed Atlas @100 mt. The following considerations can be derived:

- Solar (Figure 2): the map shows that solar irradiation is homogeneously distributed in the whole Admissible areas of country, with large solar potential. The Province with the largest solar potential is Northern Cape Province, which is also the region with the largest (in absolute terms) territory that may host solar fields. In the Province, there are areas where GTI exceeds 2.6 MWh/m^2 per year.
- Wind (Figure 3): the map shows that the Admissible areas for wind resource are limited mainly to the Northern and Western Capes. Moreover, with respect to solar, wind availability is much less uniformly distributed in the areas, ranging from locations where the average wind speed exceeds 12 m/s up to locations characterized by much lower values, close to 4 m/s.

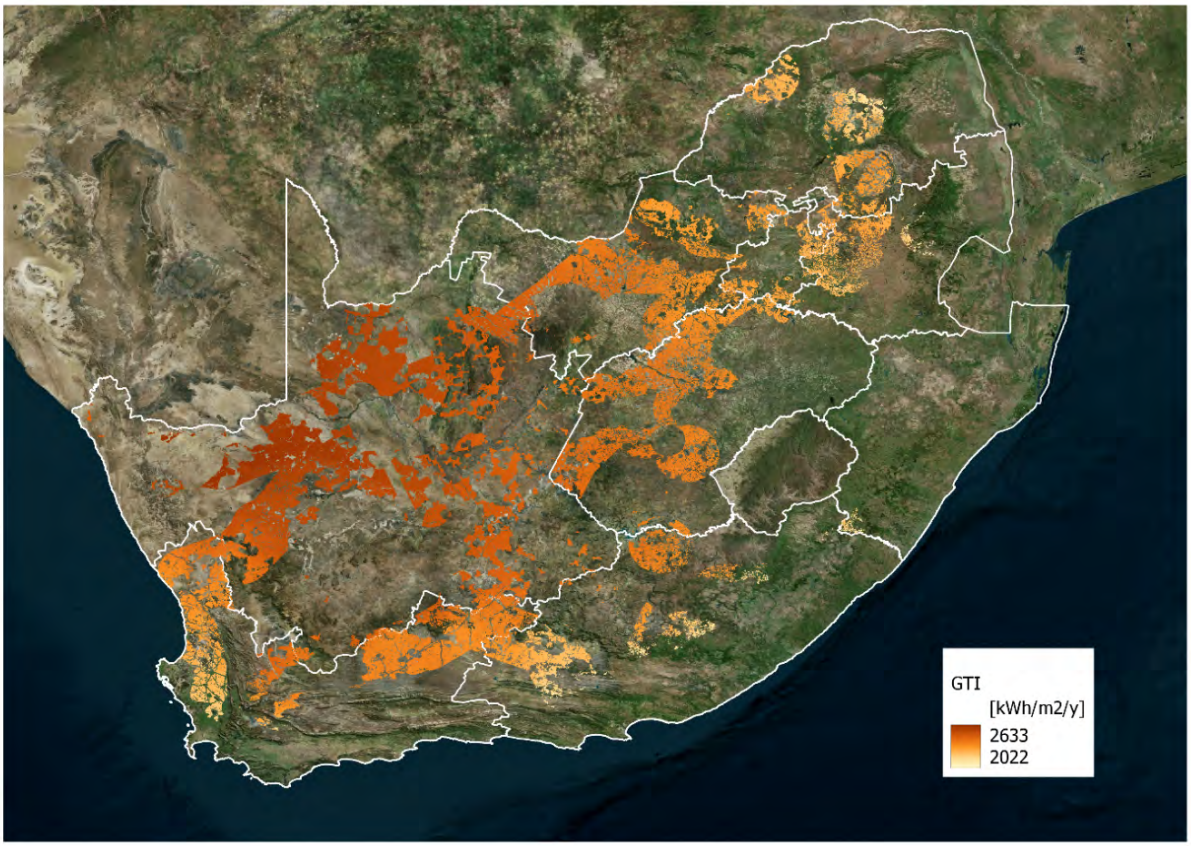


Figure 2 Visualization of the GTI Atlas.

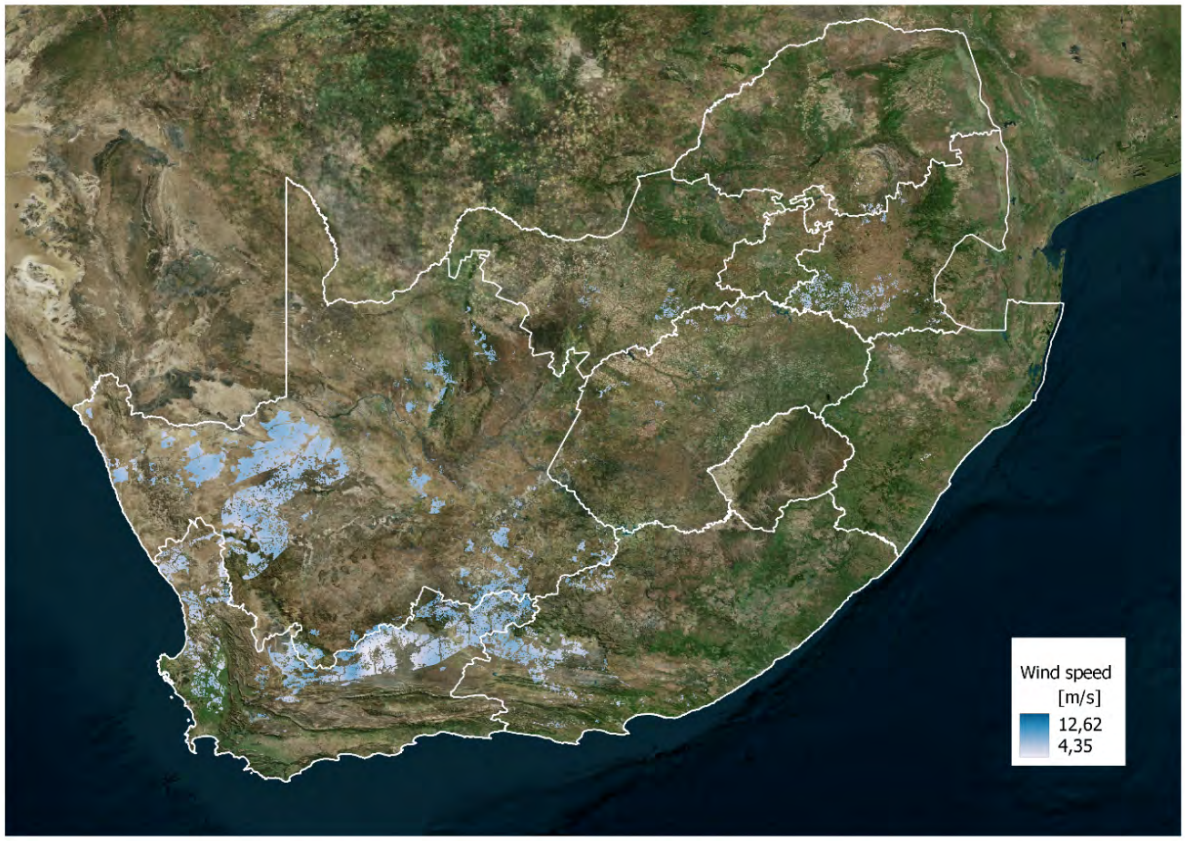


Figure 3 Visualization of the Wind Speed Atlas @100 mt.

The second analysis reported in Figure 4 and Figure 5 shows graphically, in form of histograms, the geospatial and numerical distribution of daily solar GTI and average wind speed across South Africa (in red for solar, in dark blue for wind), compared to the same only in the Admissible areas (in orange for solar, in light blue for wind).

Solar GTI raster

The comparison allows to derive the following conclusions:

- The areas selected in the SEA study are the ones with the largest availability of solar resource – i.e., the two curves are almost overlapping at the highest values of irradiation.
- The peak of probability of solar resource occurs in both the cases at the largest values of GTI, confirming what already observed from the map in Figure 2. That is, the sunnier areas in South Africa prevail on the national territory, i.e., the solar availability is high in the largest part of the country.

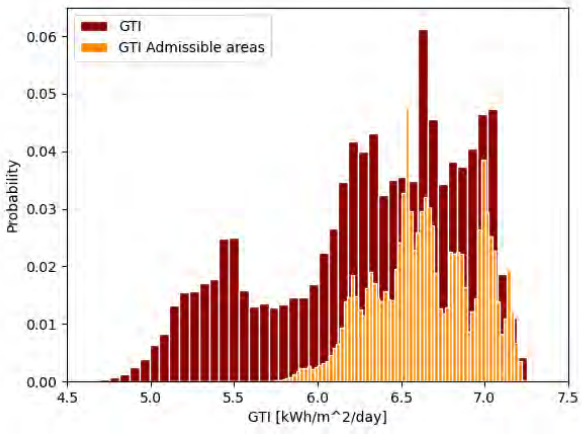
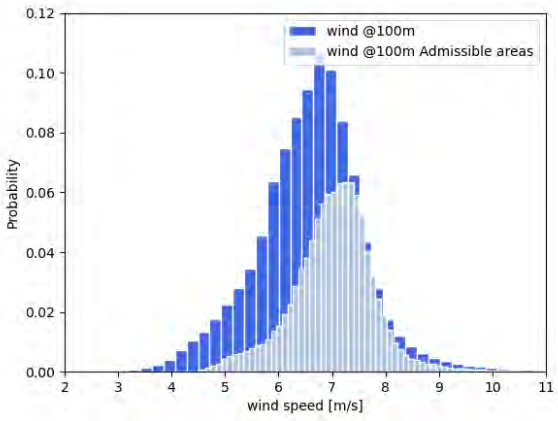


Figure 4 Probability distribution of average daily GTI

- Remarkably, not only the large availability of solar is well distributed on the whole territory but is also remarkably high. Average values of GTI among 6 to 7 kWh/m^2/day place South Africa among the countries with the highest radiation levels in the world.	
Wind GTI raster The comparison allows to derive the following conclusions: - The areas selected in the SEA study are the areas with the largest availability of wind – i.e., the two curves are almost overlapping at the highest values of wind speed. - With respect to solar resource, distribution of wind probability is closer to a Gaussian distribution, meaning that the windier areas in South Africa are limited and that the wind availability stands at "average" values in the largest part of the country. - The availability of wind resource is promising. Average values of wind speed around 7/8 m/s at 100 m make wind availability in South Africa comparable to the Norther Continental European countries.	 *Figure 5 Probability distribution of average wind speed.*

The final discussion concerns the analysis of the Weibull curves. Figure 6 reports the Weibull probability distribution of sample areas with relative low average wind speed (blue curves, with average wind = 5 m/s), medium average wind speed (orange curves, with average wind = 9 m/s), high average wind speed (green curves, with average wind = 11 m/s) at 100 m hub height. The results suggest that the lower is the average wind speed, the more uniform and constant it is during the year (the curve is squished to the left around a narrower range of wind speed). On the contrary, the curves with higher values of average wind speed have a lower probability peak and are more stretched out around a larger range of wind speed, meaning that the range of variability during the year is larger.

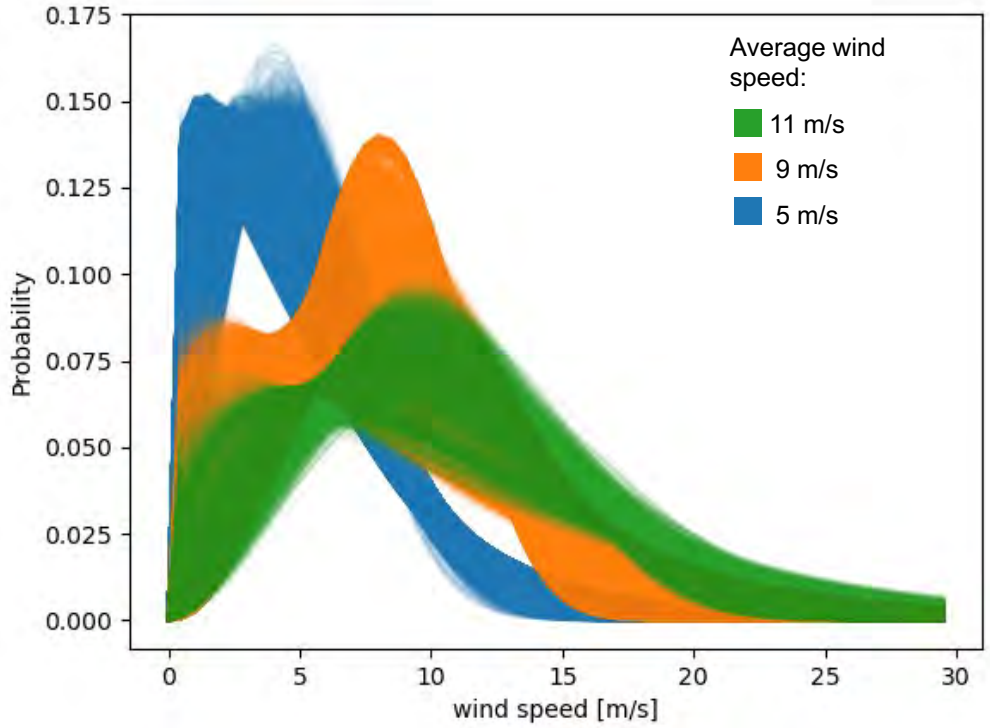


Figure 6 Weibull probability distribution of three areas. Blue curves, average wind speed = 5 m/s (IEC Class III); Orange curves, average wind speed = 9 m/s (IEC Class II); Green curves, average wind speed = 11 m/s (IEC Class I)[1].

[1] IEC Classes are explained in Section 4.2.1.

4. STEP 2: IDENTIFICATION OF RESOURCES TECHNICAL POTENTIAL (CAPACITY FACTOR ASSESSMENT)

4.1 Goal

The goal of the second step of the procedure is to evaluate the technical potential, in terms of capacity factor (CF) and annual specific energy yield per unit of power capacity installed [kWh/kWp] of solar and wind resources in the Admissible areas of South Africa. The CF indicates the percentage of time in which V-RES installations are expected to work at nominal power, while the energy yield is a measure of the equivalent hours in which V-RES installations are expected to work at nominal power.
This Step 2 translates the previously developed solar and wind Atlases into new separate Atlases reporting values of average V-RES yield and CFs in the Admissible areas. The technical potential depends on the design parameters of the components used to convert solar and wind energy into electrical energy (namely photovoltaic modules and wind turbines) which need to be integrated in the Atlases creation.

4.2 Procedure

The adopted procedure follows the steps described in detail in the following paragraphs aimed at collecting the input data, process them, and create the desired output.

4.2.1 Input data processing

Data used for this step of the procedure are a combination of geospatial data, both derived from Step 1 and downloaded from online data providers, and of technical data of components.

- *Photovoltaic Power Output (PVOUT)*: it is the expected specific annual energy output per installed capacity of 1 kWp of solar. The Global Solar Atlas [1] of the World Bank provides a PVOUT raster layer, computed for a generic crystalline-silicon PV module inclined at optimal tilt angle, with around 1 x 1 km^2 resolution. The unavailability of open solar databases mapping the solar resource on the orthogonal plane, the main analysis does not consider at first the simulation of a PV with bifacial modules combined with tracking system. This solution is subject to sensitivity analysis (Ⓢ) in Section 8, by applying an average improvement of 23% on the CF/Energy Yield of solar PV in each pixel, in order to test bifacial modules combined with tracking system based on the experience of RES4Africa (through developers) in South Africa.

- *Wind turbine power curve*: it provides the values of expected power output of a turbine as a function of the wind speed at hub height. It is characterized by:
    a) *v-cut_in*: the minimum wind speed at which a turbine starts producing
    b) *v-cut_out*: the maximum value of wind speed, after which the turbine stops producing
    c) *v-rated*: it is the wind velocity at which the turbine starts producing at rated power. Between the *v-cut_in* and the *v-rated,* the turbine increases gradually the power output with a curve depending on the turbine model, approximately growing with the cube of the wind speed.

Three classes of turbines have been considered in the analysis, corresponding to the three wind classes identified by the International Electrotechnical Commission (IEC), whose parameters are reported in Table 2. Their specific power curve has been downloaded from the Wind Integration National Dataset Toolkit [3] and shown in Figure 7.

Table 2 Parameters of IEC wind turbine classes.

IEC Wind Class	Annual average speed [m/s]	50-year Return Gust	V cut-in [m/s]	V rated [m/s]	V cut-out [m/s]
I	10	70	3	15	25
II	8.5	59.5	3	13	25
III	7.5	52.5	3	12	22

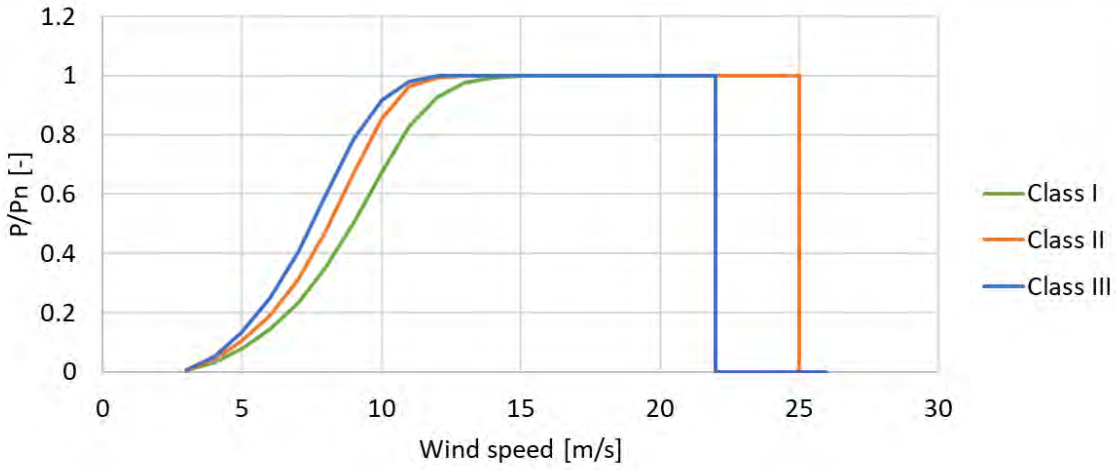


Figure 7 Wind turbine power curves, according to Wind Integration National Dataset Toolkit (reference P_{nom} set at 2 MW) [3].

4.2.2 Solar technical potential

Assuming that the PV modules are installed at their optimal tilt angle, the equations that allow to convert the GTI into energy yield and capacity factor are the following.

$$Energy\ yield\ = \sum_{t=0}^{8760} \frac{GTI(t) \cdot \eta \cdot PR(t) \cdot Area}{P_{nom}} \left[\frac{kWh}{kWp}\right]$$

$$CF = \frac{Energy\ yield}{8760}$$

Where:

- η is the conversion efficiency of the modules in standard test conditions (irradiance of 1000 W/m^2, T_{amb}=25°C).
- $PR(t)$ is the performance ratio, which considers the effective efficiency of solar panels at actual not-standard operating conditions.
- P_{nom} is the nominal power of PV modules, which corresponds to the power produced with a certain surface $Area$ and in standard conditions.
- $PR(t)$ is a time dependent variable, which accounts for the reduction of modules efficiency with the increase of module temperature, dependent in turn on the ambient temperature and on the irradiance.

Since the irradiation and temperature data available with high spatial resolution are provided only as yearly averages, applying the formula for computing Energy yield would cause several huge approximations. For this reason, the PVOUT layer from the Global Solar Atlas, previously described, is used as reference for the energy yield. The indicator is computed in Global Solar Atlas considering the following parameters:

- Total losses due to dirt, cabling, inverter and availability: 8.9%
- Nominal Operating Cell Temperature (NOCT): 46.2 °C
- Temperature coefficient: -0.45%/°C

Those parameters contribute to compute the $PR(t)$ at different cell temperatures.
The output layers for PV energy yield and CF are thus obtained by cropping the PVOUT layer with the Admissible areas as described in Step 1.

4.2.3 Wind technical potential

Starting from the Weibull distribution definition, reported in the previous chapter, it is possible to derive the cumulative distribution function, that is the probability of having a wind velocity lower than a certain value v_i.

$$F(v_i) = 1 - e^{-\left(\frac{v_i}{A}\right)^k}$$

The probability that the wind velocity belongs to a defined interval of values can consequently be defined as:

$$F(interval) = F(v_{i+1}) - F(v_i)$$

Since the power curve is available as a discretized set of P-v couples, rather than a continuous function, the energy output can also be derived as the summation of the power output at each wind speed interval $P(v_i)$ multiplied by the probability of occurrence of that interval. The annual average power output of a generic turbine with a defined power curve can be then expressed as:

$$Energy\ yield = \sum P(v_i) \cdot F(interval) \cdot 8760$$

$$CF = \frac{Energy\ yield}{8760}$$

The choice of the wind turbine class, and hence of the power curve to be utilized has been made based on the average wind speed for each pixel of the wind Atlas. According to IEC classification reported in Table 2, the indicator used to associate each pixel to a candidate IEC class-turbine is the annual average speed:

- All the pixels with an average wind speed lower or equal than 8.5 m/s have been associated to a curve of IEC class III.
- The ones with wind speed lower or equal than 10 m/s to IEC class II.
- The remaining to IEC class I.

This hypothesis is of course a simplification, that would not apply alone when designing a wind farm for a selected location. However, it has been considered as an acceptable discriminating factor for this study that looks at a global (i.e., whole country) assessment of the resource, without local design implications.

The above formulas have been applied directly to compute energy yield and CF at 100 hub height. To make the analysis more comprehensive, those indicators have been computed also for hub heights of 90m ,120m and 140m. Since the WASA website did not provide data related to 90m 120m and 140m,

which are common hub heights for wind turbines in South Africa (as per feedback provided by the O&M working group in SAWEA), some additional data processing was required. Wind speed at a specific altitude *x* can be computed with the power law formula, knowing the wind speed at altitude *y*:

$$v_x = v_y \cdot \left(\frac{x}{y}\right)^{\alpha}$$

α is called the shear coefficient and it is a parameter that depends on the roughness and shape of the terrain on the ground, the coastal location and the stability of the air. It is computed for each pixel of the Atlas by inverting the formula, knowing from the data the value of wind speed for 50, 100 and 150m, as retrieved in Step 1.

From there, the energy yield is computed considering, for each interval of velocity $(v_{y_{i+1}} - v_{y_i})$, at an altitude with known Weibull parameters, the power in the power curve at v_x, computed through the power law formula:

$$Energy\ yield = \sum P\left(v_{y_i} \cdot \left(\frac{x}{y}\right)^{\alpha}\right) \cdot F(interval) \cdot 8760$$

For each class of turbine, and for the four hub heights of 90m, 100m, 120m and 140m, the annual specific energy yield as well as the capacity factor have been calculated with a spatial resolution, given by the input files of Step 1, of 0.025 longitude/latitude degrees, i.e., approximately 250 m.

4.2.4 Output

The outputs of the Step 2 are delivered as follows:

1. *Solar Production Atlas*: one (1) raster file (.tiff) for energy yield and one (1) raster file (.tiff) for CF with 1 x 1 km^2 resolution.
2. *Wind Production Atlas*: four (4) raster files (.tiff) with energy yield @90m, 100, 120m and 140m and four (4) raster files (.tiff) with CF @90m, 100 ,120m and 140m.
3. *Comprehensive Atlas*: one (1) vector file with grid at 5x5 km^2 resolution and both the attributes of Solar and Wind Production Atlases.
4. *Html map*: file composed of 4 interactive maps showing the value of Energy Yield and CF od PF and Wind @100m.

4.3 Results and discussion

The next graphs report an overview of the V-RES exploitability in South Africa, showing graphically the geospatial and numerical distribution of annual solar and wind energy yields across South Africa.

Solar Yield	**Wind Yield**
The results in Figure 8 reflect the outcomes of Step 1, as discussed in Section 3.3. The solar	The results in Figure 9 report the wind energy yield at 4 hub heights. Also this indicator

exploitability is high in the country, with the highest values reached in the majority of the Admissible areas of the whole national territory.

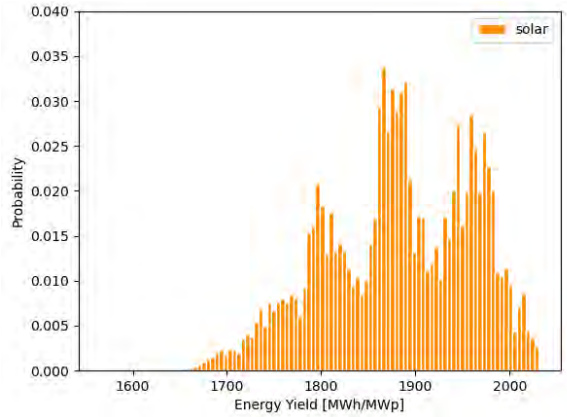


Figure 8 Solar energy yield.

confirms what already identified in Step 1: respect to solar resource, the wind exploitability stands at "mean" values in the largest part of the country at 90 m and 100 m of hub heights. Also, the amplitude of the energy yield range for wind is very large (e.g., 2000-5000 h for wind, compared to 1700-2000 h for solar), meaning that wind resource exploitability is very variable on the national territory.

At 120 m and 140 m of altitude, the distributions seem stretched to the right. Considering that the average wind distribution of an area does not considerably change in "bell" shape at the various altitudes (see Figure 10), this stretching effect is attributable to the fact that at 120 m and 140 m, the *v-cut_out* of the reference IEC Class I/II/III turbines (see Figure 7) limits the potential exploitation of the wind resource (mainly IEC Class III, as discussed in Figure 14 below). Of course, in case of local design of a wind farm, this consideration may suggest that IEC Class II and I may be investigated for application at hub heights higher than 120 m, since they have a *v-cut_out* higher than IEC Class III.

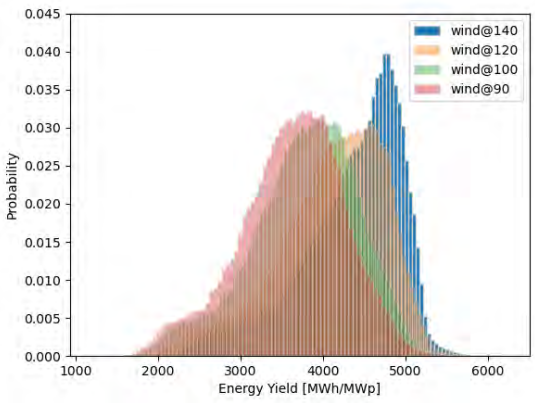


Figure 9 Wind energy yield at different altitudes.

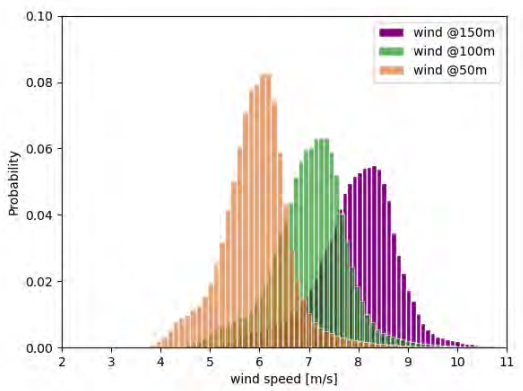


Figure 10 Probability distribution of average wind speed at 50m, 100 m and 150 m.

Figure 11 Distribution of PV and wind energy yield

The next results relate the energy yield of solar PV and wind in relation to the primary resource availability

Scatter plot solar yield vs GTI

As expected, the figure shows a linear relation between the solar yield and the GTI. Also, the graph clearly reveals the effect of the operating temperature that decreases the energy yield of PV systems.

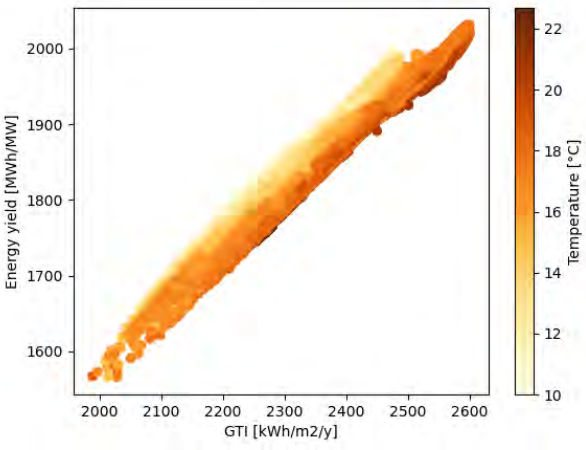


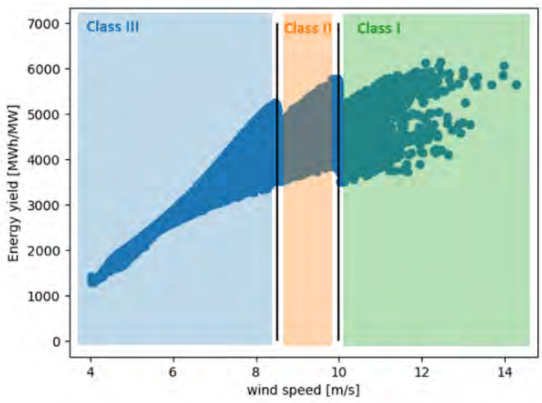
Figure 12 Solar yield vs GTI.

Scatter plot wind yield vs average wind speed

In case of wind, the relation between wind yield and wind speed is not linear, since the calculation of the energy yield pass through the power curves that have not linear behaviours (see Figure 7).

Also, at the interfaces between Class III, II, I there is a kind of step decreases of performances. This can be justified by the fact that the selection of one IEC Class respect to another is given by the average velocity as unique discriminating fact (see discussion in Section 4.2.1). Of course, there are other discriminating factors that justify the selection of the most appropriate Class, such as the robustness/structural resistance to higher wind speeds that allow to extend the range of wind speed exploitability at the right, but at the expenses of a decrease of performance.

Another interesting outcome is that the higher wind speed (i.e., moving to the right of the graph), the larger is the range of energy yield. This indicates that the locations with higher average wind speeds have a distribution of wind speed during the year that is more variable. This is also suggested by looking at Figure 6, reporting the Weibull curves for the three IEC Classes, where it emerges that the curves of IEC Classes I and II differ more in

	shape despite the same average wind speed considered within the same class.  *Figure 13 wind yield vs average wind speed.*

Focusing on wind, Figure 14 below reveals that for most of the Admissible areas, IEC Class III turbines seem the best candidates on the national territory. This is a direct result of the fact that the discriminating factor adopted for associating each pixel to an IEC class has been the average annual wind speed, which in South Africa is close to 7 m/s, and so falling within the range of applicability of IEC Class III. As also reported in Section 4.2.3, this hypothesis has been adopted for identifying a univocal criterion to perform this global analysis on the whole country, and the obtained results are not meant to have local design implications.

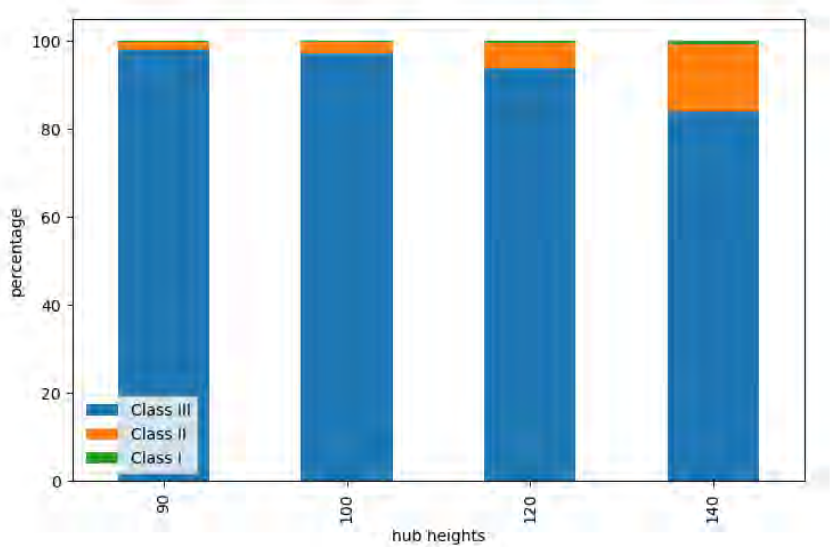


Figure 14 Percentage area of the three wind classes at different hub heights

A final analysis has been performed to assess the reliability of the CF results calculated through the procedure described above in 4.2.3 from the wind data from the WASA database, respect to the CF values directly download form the Global Wind Atlas [4] of the World Bank at 100 mt hub height (the only available height from the Global Wind Atlas). Since class IEC III is the one resulted to be the most suitable candidate for almost the whole territory (see Figure 14), it has been considered for the

comparison. The graph of Figure 15 shows the results of the comparison, with the following considerations:

1) The light blue distribution “CF IEC 3” represents ratio of the CF calculated from WASA to the one downloaded from the Global Wind Atlas. The distribution has an average value of 1.2, meaning that, on average, the results of CF calculated with the procedure described in Section 4.2.3 from the wind data from the WASA show 20% higher values than the CF downloaded from the Global Wind Atlas.
2) The reason for this bias has been investigated and it has been attributed to these concurring factors:
    1. Data used from WASA are noticeably different from the Global Wind Atlas. This is confirmed by the dark blue distribution “wind speed”, which represents the ratio of the wind speed data retrieved from WASA as in Step 1 of the methodology to the ones from the Global Wind Atlas. It can be noticed a bias higher than 1, with an average value of 1.1, meaning that, on average, the WASA data are 10% higher values than the data Global Wind Atlas.
    2. The Global Wind Atlas do not report the details and methodology used for defining the wind power curve adopted to make the analysis. Since the power curve highly depends on the different turbine models, it is highly probable that the curved adopted by the Global Wind Atlas is not the same of the standard one used in the study (derived from the Wind Integration National Dataset Toolkit, as per Figure 7).

    The two factors together can explain and justify the bias between the two set of results.

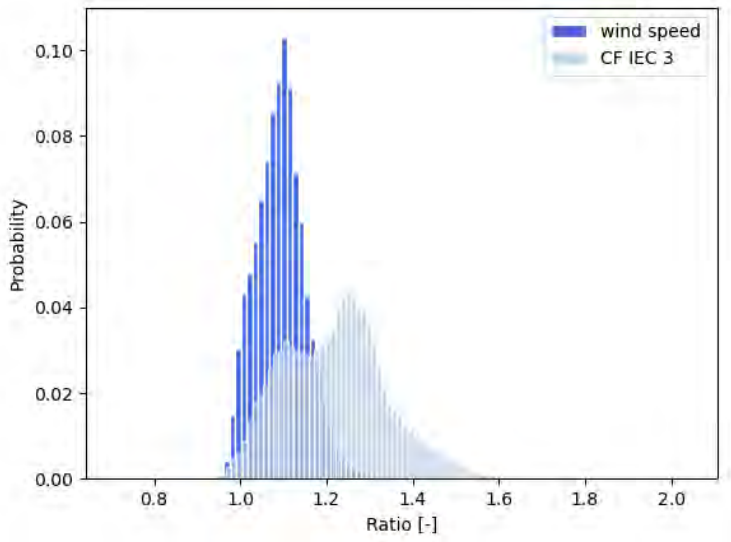


Figure 15 Probability distribution of ratio between WASA and Global Wind Speed data

Given these differences in the two results and being the CF/Energy Yield a crucial variable with a relevant impact on the results, its value is subject to sensitivity analysis (Ⓢ) in Section 8. In particular, the values calculated in this Step 2 are multiplied all over the pixels by a scale factor that bring backs the obtained values of CF/Energy Yield to the ones of the Global Wind Atlas and also aligned with the indications of RES4Africa based on its experience (through developers) in South Africa (see sensitivity analysis in Section 8).

5. STEP 3: ANALYSIS OF V-RES AVAILABILITY

5.1 Goal

This step builds upon the quantitative results of the previous Step 1 and Step 2, in order to provide an overview and analytical discussion of the integrated V-RES potential and availability as disaggregated by South African Provinces.

5.2 Analysis

A geographical representation of the absolute potential of V-RES in the South African Provinces is reported in Figure 16 and Figure 17.

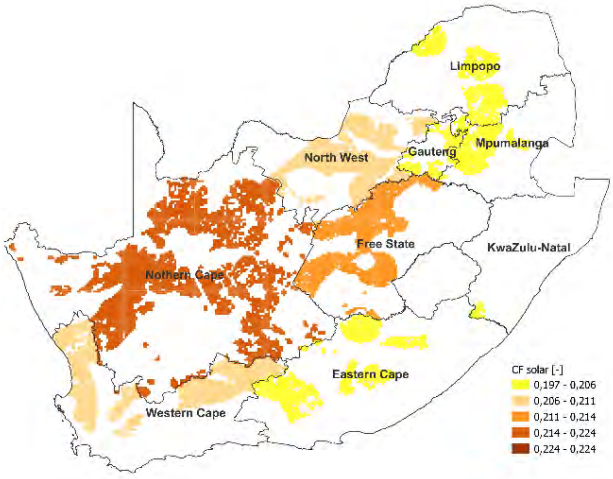


Figure 16 Average CF [-] of PV plants in the 9 provinces (geographical representation). This map is subject to sensitivity analysis (Ⓢ).

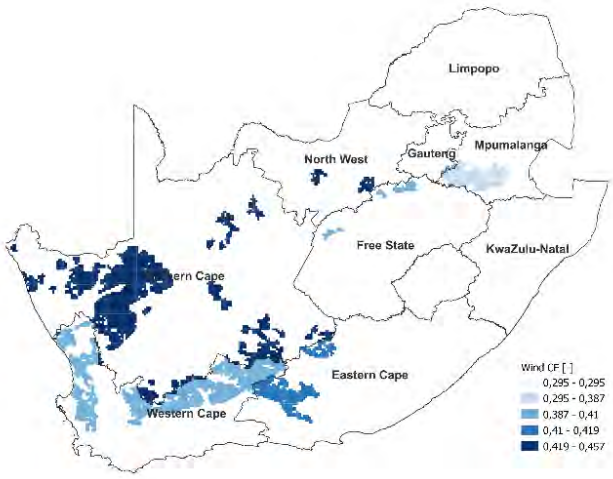


Figure 17 Average CF [-] of wind plants @ 100m in the 9 provinces (geographical representation). This map is subject to sensitivity analysis (Ⓢ).

Since V-RES exploitability is subject to land restrictions, the two figures above should be read in conjunction with a representation of the Admissible areas, in order to properly assess the actual potential of V-RES in one Province respect to another. This is done through next four figures: the first one (Figure 18) provides the average capacity factor, while the second one (Figure 19) reports the Admissible areas to install solar or wind plants. Figure 20 and Figure 21 plot the solar and wind CFs with respect to the available Admissible areas by Province. At glance, the following conclusions can be derived:

1. As also reported in Step 1, solar potential is uniformly well distributed in the whole country, while wind is less uniform, reaching the highest values in North West and Northern Cape, and the lowest ones in Limpopo and KwaZulu-Natal.
2. In terms of exploitability, Northern Cape and Western Cape are the two Provinces with the largest availability of Admissible areas.
3. Combining the two, it can be concluded that form a generation perspective, the two most attractive Provinces for V-RES installations (both wind and solar) are Northern Cape and Western Cape, followed by Free State (mainly solar), North West (mainly solar), Eastern Cape (both wind and solar), and Limpopo (mainly solar).

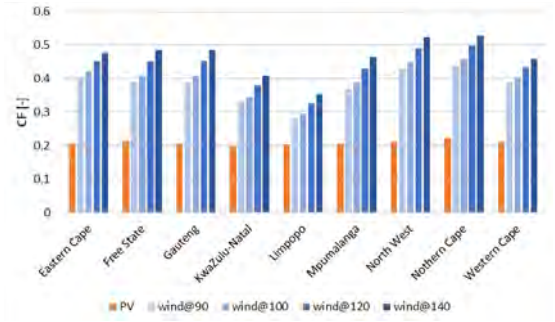


Figure 18 Average CF [-] of wind and PV plants in the 9 provinces.

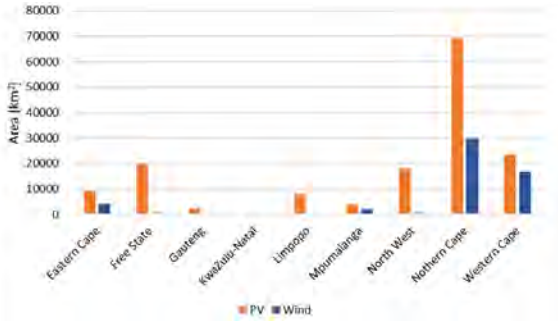


Figure 19 Available surface area [km²] for PV and wind plants installation in the 9 provinces.

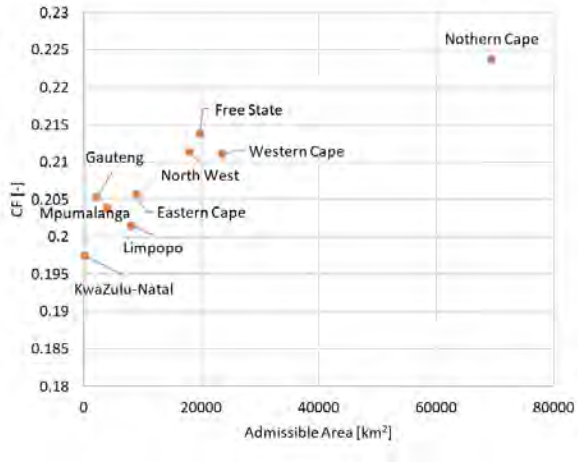


Figure 20 Solar CF vs Admissible area [km²] in the 9 Provinces.

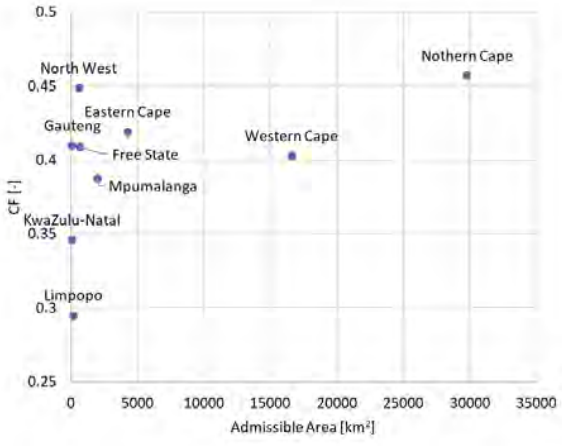


Figure 21 Wind @100m hub height CF vs Admissible area [km²] in the 9 Provinces.

5.2.1 Considerations on V-RES variability

The weather-driven variability of V-RES represents the main source of concern for their optimal planning and integration within the power system. The international literature and best practices around the world have demonstrated that fostering deep integration of V-RES into the grid is feasible and manageable, regardless the intrinsic variable nature of V-RES due to supply fluctuation and uncertainty (see [5], for example). One of the main instruments to smooth the effect of weather-driven short-term variability, and to reduce the need of a large conventional generation fleet as backup and a massive deployment of storage, is the diversification of V-RES generation fleet. In fact, as more and more V-RES of different nature are integrated into the system, not only short-term fluctuations in the generation tend to be dampened by the simultaneous effect of multiple VRES plants, but also the "capacity credit"[2] of V-RES tends to increase by balancing PV and wind capacity. The increase of capacity credit could be also pursued by increasing the contemporaneity of V-RES output with load demand, by relying both on the "natural" coincidence (e.g., PV output during daily peak hours) or on a "forced" one (through peak-load shifting with storage).

In South Africa, V-RES variability can be particularly relevant, given the challenges of capacity constraints that the current grid infrastructure is experiencing during operation. A bottom-up approach able to

[2] The capacity credit concepts indicate the extent to which VRES need conventional generation for compensating the unavailability during the year (i.e., due to a low-capacity factor) and the short-term fluctuations due to the weather variability.

optimize the generation portfolio at each substation, minimizing the impact of V-RES on the grid while considering local production and demand peculiarities may be beneficial for V-RES integration in the country.

In particular, to facilitate V-RES integration into the system, the identification of the optimal V-RES connected to the same substation should consider: (1) the limitation of the overproduction subject to power curtailment during off-peak hours/hours with large V-RES availability, and (2) the limitation of unmet load during the peak-hours/ hours with low V-RES availability. This would introduce a further optimization criterion for V-RES appropriate localization, beyond the criteria selected for this study (please see next Step 4 in Section 6).

Being this analysis out of the scope of this study and requiring it an additional massive set of data (e.g., time-series of solar and wind resources/power output with at least hourly resolution, and load data at substation level), we recommend it as a further step in Section 9. The analysis could be extended also at a Country level perspective, to assess how different V-RES production patterns in the Western and Eastern parts of the countries could combine to optimally follow the load demand and the necessities of the system, thus increasing their capacity credit.

To provide RES4frica and Eskom with preliminary considerations towards this analysis, two additional analyses are presented below.

As a first step towards this analysis, the next figures report for each Province an indicator of V-RES variability against the average CF:

- For wind, the chosen parameter is the average (Figure 22) and maximum (Figure 23) standard deviation of the wind velocity in the Province territory, derived from the Weibull distribution for each pixel of each Province. The WASA database does not specifically reports the time-resolution of the data used for calculated the Weibull for each pixel. Supposing that the basis of calculation has been the *WASA1 Wind time series* data (or updates of it), the time resolution for that set of data is 1-hour. If so, the variability expressed by the standard deviation in Figure 22 and Figure 23 is a proxy of the hourly volatility of wind resource. A high average standard deviation indicates that the wind resource has a high hourly variability during the year, while a low standard deviation means a more uniform wind resource across the year.
- For solar, the chosen parameter is the average standard deviation of the average monthly radiation (Figure 24) in each Province territory. This value provides indication of the *seasonal* variability of the solar resource in a year. A high average standard deviation indicates a high monthly variability of solar resource across the year, while a low standard deviation indicates a more uniform solar resource through the months.

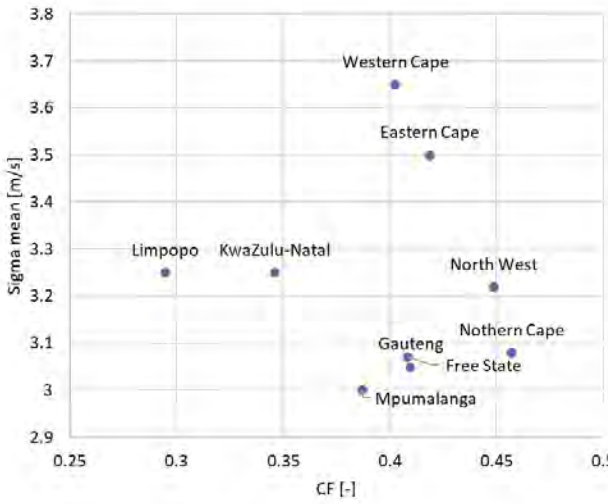


Figure 22 Average wind Standard Deviation @100m hub height vs CF.

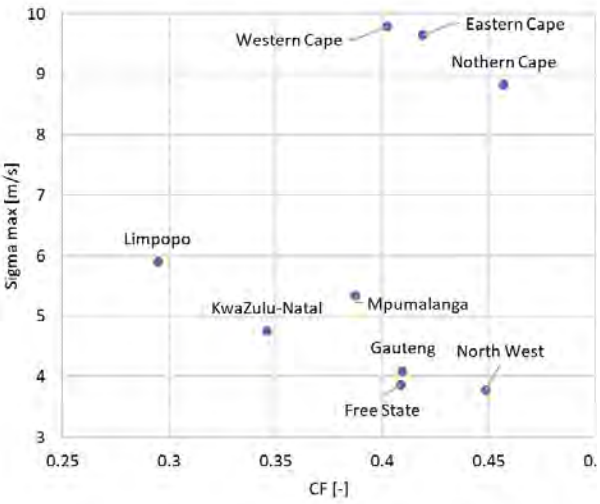


Figure 23 Maximum wind Standard Deviation @100m hub height vs CF.

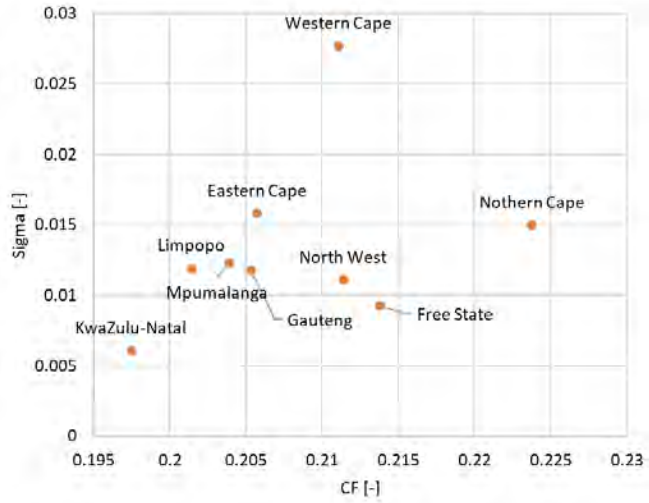


Figure 24. Average solar Standard Deviation (monthly basis) vs CF.

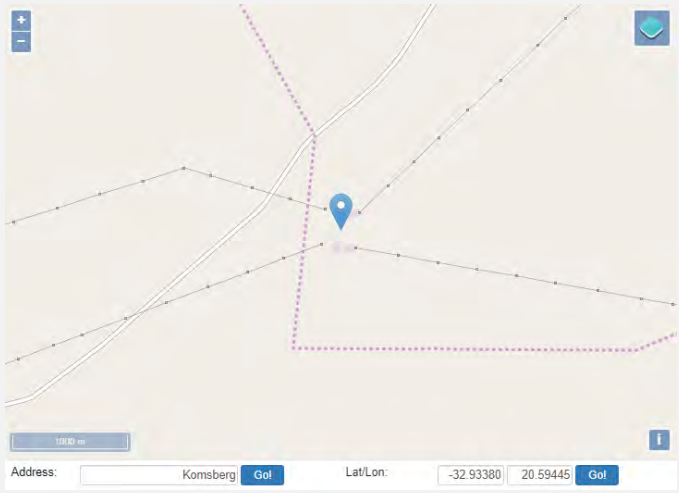
The results do not allow to derive any meaningful trendline that links CFs with the intrinsic variability of V-RES. Nevertheless, it provides these preliminary considerations:

- Eastern Cape and Western Cape are the two provinces where both the wind and sun variability indexes assume the largest values (despite referring to two different time frames)
- Northern Cape has a lower average wind variability index (Figure 22), but a very high wind maximum variability index (Figure 23), suggesting that there are areas (i.e., pixels) characterized by very high volatility and others where wind velocity is more uniform.
- Eastern Cape, Western Cape, and Northern Capes, which have high variability of resources and the highest CF in the Admissible areas, appear to be the most promising Provinces for studying the integration of sun and wind and their coincidence with peak demand (at substation level), as recommended above.

As a second step in the V-RES variability analysis, an energy-based case-study is reported. This case, identified with RES4Africa and reported in the next box, allows to assess the benefits of PV-Wind integration at substation level.

CASE STUDY: testing PV-Wind integration at Komsberg S/S

This box reports the case-study identified with RES4Africa, which aims at evaluating the benefits of PV-Wind integration at local level, namely at Komsberg S/S (Lat. -32.93380 / Lon. 20.59445). The case study is particularly representative since it is located in Western Cape, one of the Provinces with the largest degree of variability of V-RES together with highest CF.



The following time-series of data are used for V-RES:

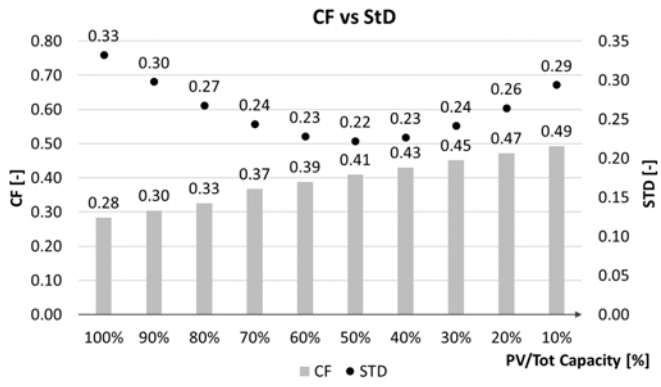
	PV	**Wind**
Source	PVGIS[3]	Renewable.ninja[4] [6]
Ref. Capacity	1 MW	
Ref. Year	2019	
Dataset	PVGIS-SARAH2	MERRA-2 (global)
Technology	- Crystalline silicon - Tracking: inclined axis - Optimized slope - 14% System loss	- 140m hub height - Siemens Gamesa SG 4.5 MW 145 m (D)
Output	Hourly power production in [MW]	

The national load demand in 2022 provided by ESKOM and used in the TDP2021 is used as a proxy of the representative 1 MW-peak load profile at the S/S. In particular, the yearly load demand is normalized by dividing it to the annual peak load and multiplying by 1 MW.

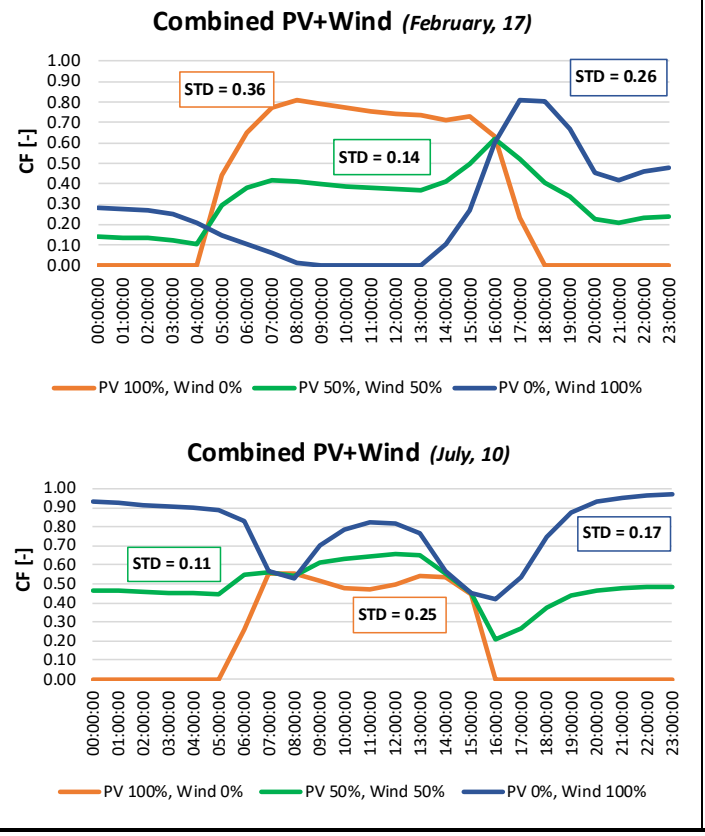
The results are elaborated and presented in the form of 4 different outputs:

[3] https://re.jrc.ec.europa.eu/pvg_tools/en/
[4] https://www.renewables.ninja/

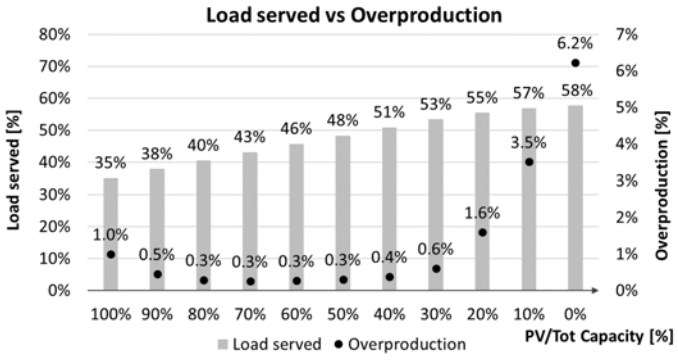
1. Average CF with its standard deviation (StD) for different V-RES combinations: the fraction of total capacity covered by PV ranges from 100% to 0%. The total capacity of V-RES (PV + wind) = 1 MW.
2. A graphical representation of the hourly combined CF with its standard deviation for the integrated V-RES capacity for a typical summer and winter day. The total capacity of V-RES (PV + wind) = 1 MW. The fraction of total capacity covered by PV ranges from 100% to 0%.
3. Load served [%] vs Overproduction [%] of the integrated V-RES capacity from 100% to 0% PV integration. Total capacity = 1 MW.
4. Optimized integrated V-RES capacity, able to minimize the yearly sum of hourly unserved load and overproduction.

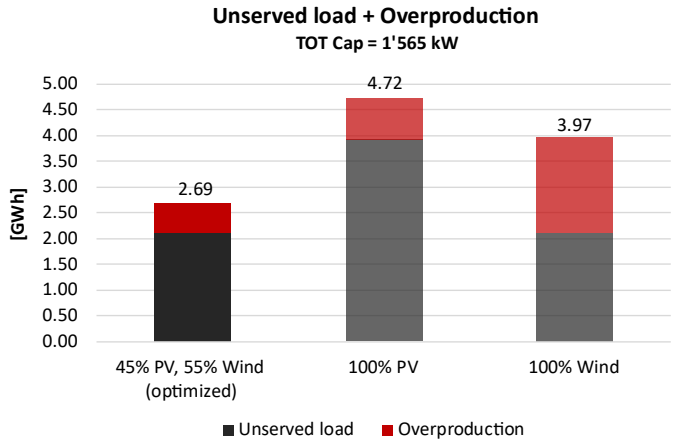


In the selected location wind maximizes the power production all over the year, due to a higher average annual CF. Nevertheless, the figure confirms that the integration of Wind and PV minimizes the variability during the year (minimum StD), which reaches its minimum with a 50:50 integration.



Practically speaking, the previous consideration means that integrating VRES allows to have a flatter production during the year, with smoother hourly variations. This is displayed by the two figures reporting the combined CF for a summer and a winter day, confirming that the solution with the highest Wind and PV integration is the one with the lowest standard deviation and also the flattest profile.

<table>
<tr>
<td>
</td>
<td>The graph on the left reports the two following indicators:
- Load served: the percentage of load served, intended as the fraction of the hourly 1 MW-peak load covered by the hourly combined PV+Wind production over the year.
- Overproduction: the percentage of overproduction, intended as the fraction of the combined PV+Wind production that overcomes the hourly 1 MW-peak load over the year. It can be intended as a proxy of the curtailment.

As it is clearly visible, increasing the Wind penetration in the V-RES mix improves the percentage of load served, but at the expense of a higher overproduction, which starts to increase exponentially after a 70% wind integration.</td>
</tr>
<tr>
<td>
</td>
<td>The final analysis concerned the calculation of the optimal total V-RES integrated capacity able to minimize the summation of the unserved load (i.e., the opposite of the previously used “Load served”) and the overproduction.

The result is the following: the optimal integrated capacity to satisfy the representative 1 MW-peak load profile is equal to 1.565 MW, composed for the 45% by PV and 55% by Wind. As displayed in the figure, the same total capacity composed by only PV or Wind causes a higher unserved load and overproduction.</td>
</tr>
</table>

5.2.2 V-RES analysis by Province

To provide the reader with a more detailed analysis, the following sheets show a detail for each Province, divided into their district municipalities. For each table, the following information are provided:

- *Table with summary indicators*:
    1. Admissible area for V-RES: total surface area where PV or wind plants could be installed, with the percentage value with respect to the total province area.

2. Area exploitable by wind: areas where wind is exploitable within the total Admissible area for V-RES.
3. Area exploitable by solar: areas where solar is exploitable within the total Admissible area for V-RES.
4. Average PV CF: the average Capacity Factor for solar in the Province.
5. Average Wind CF @90/100/120/140m: the average Capacity Factor for wind in the Province, as calculated at the different hub heights.

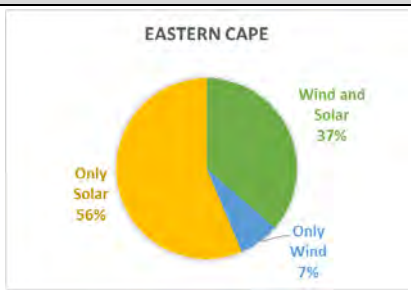
- *Pie chart*: the chart reports the subdivision of the Admissible area for V-RES into the area where only PV plants could be installed, where both wind and PV plants are suitable, and where only wind can be installed.
- *CF maps disaggregated by district municipalities*: the four blue maps show the average capacity factor of wind resource at the hub heights of 90,100, 120 and 140m, disaggregated by district municipality. The orange map shows the average capacity factor of solar resource in each district municipality. The blue- and orange-coloured backgrounds shall be intended as representative of the CFs in Admissible areas only (the black overlapping shapes).
- *Volatility indicators*: for the wind resource, it is composed by two graphs:
    1. A raster map showing, for each province, the geographical distribution of the standard deviation of the wind velocity in the territory. A high standard deviation means that the wind resource varies a lot during the year, while a low standard deviation means a wind resource more uniform during the year.
    2. A histogram with the probability density function of the standard deviation. The position of the peak on the x-axis determines whether the wind resource in the Province show low (if the peak is shifted on the left) or high (if the peak is shifted on the right) variability during the year. The amplitude of the curve indicates if such variability degree is similar in the whole Province (narrow curve) or irregular (flattened curve).

  For solar resource, since an equivalent “Weibull” distribution does not exist, and the only available data are the average monthly CFs derived from the Global Solar Atlas, the volatility indicators are represented in a graph showing the monthly CFs along the year. A flatter curve means a less variable sun radiation during the year, while a “seesaw” curve means a more variable sun radiation during the year.

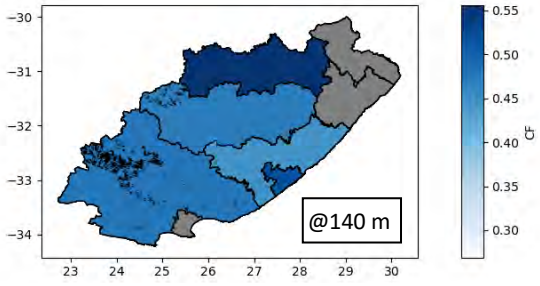
EASTERN CAPE

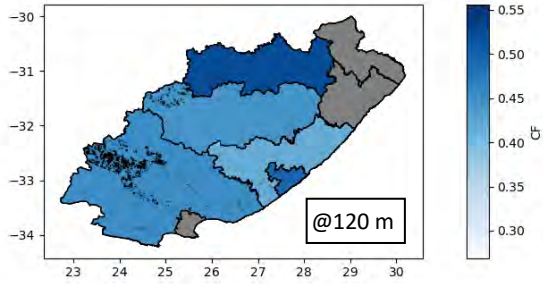
Summary Indicators	
Admissible area for V-RES:	9767 km^2 (6%)
Area exploitable by wind:	4263 km^2 (3%)
Area exploitable by solar:	9058 km^2 (5%)
Average PV CF (Ⓢ)	0.21
Average Wind CF @90m (Ⓢ)	0.40
Average Wind CF @100m (Ⓢ)	0.42
Average Wind CF @120m (Ⓢ)	0.45
Average Wind CF @140m (Ⓢ)	0.48

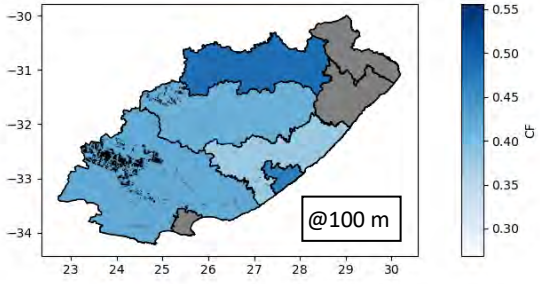
Pie chart

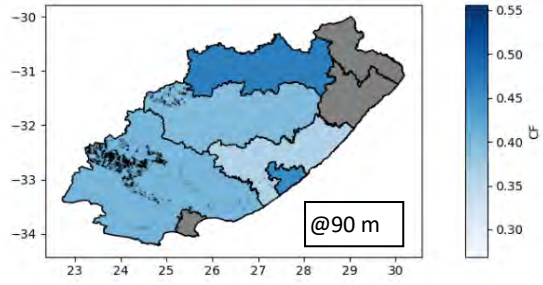


CF maps disaggregated by district municipalities (wind) ****blue colours as representative to the Admissible areas only***

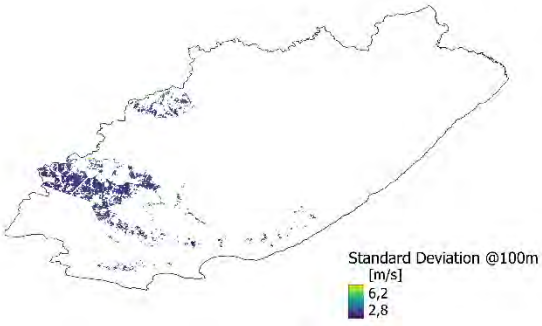


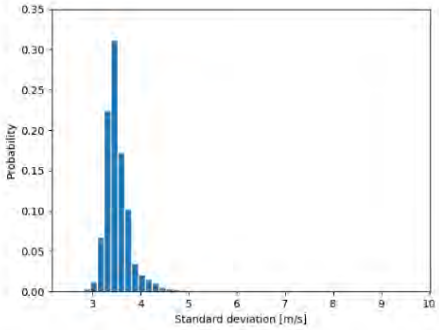




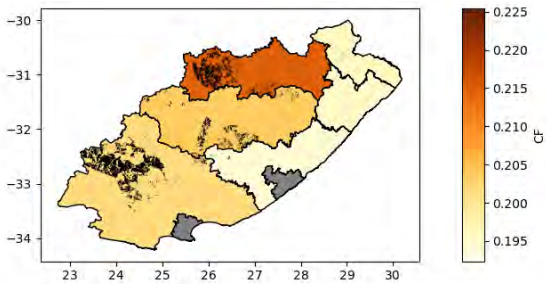


Volatility indicator (wind)

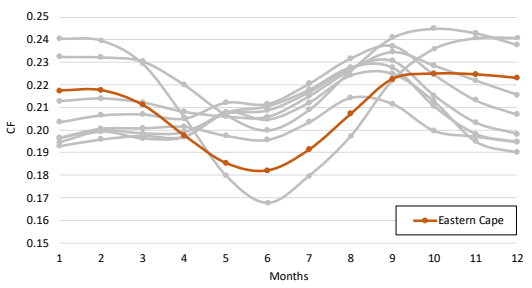




CF maps disaggregated by district municipalities (solar)
****orange colours as representative to the Admissible areas only***



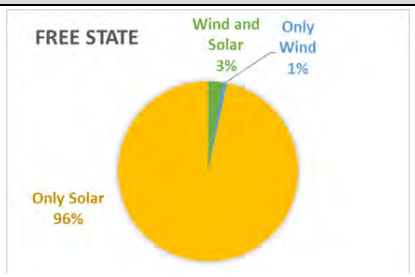
Volatility indicator (solar)



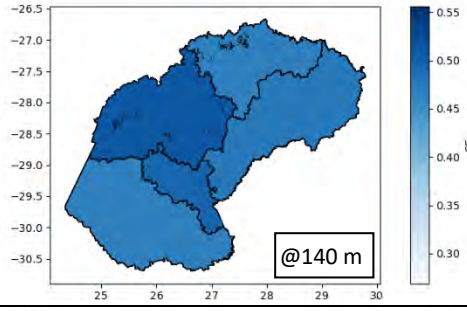
FREE STATE

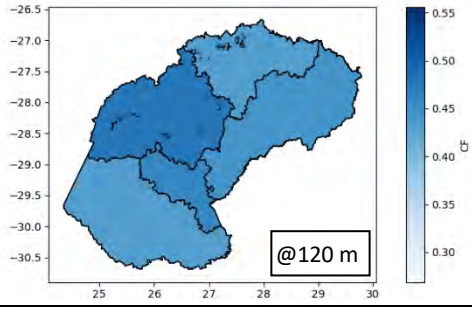
Summary Indicators	
Admissible area for V-RES:	19958 km^2 (15%)
Area exploitable by wind:	675 km^2 (1%)
Area exploitable by solar:	19820 km^2 (15%)
Average PV CF (Ⓢ)	0.21
Average Wind CF @90m (Ⓢ)	0.39
Average Wind CF @100m (Ⓢ)	0.41
Average Wind CF @120m (Ⓢ)	0.45
Average Wind CF @140m (Ⓢ)	0.49

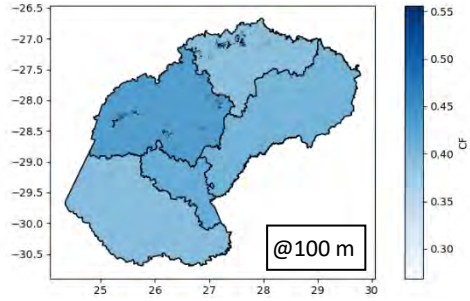
Pie chart

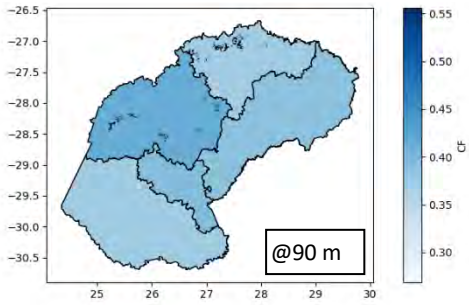


CF maps disaggregated by district municipalities (wind) ****blue colours as representative to the Admissible areas only***

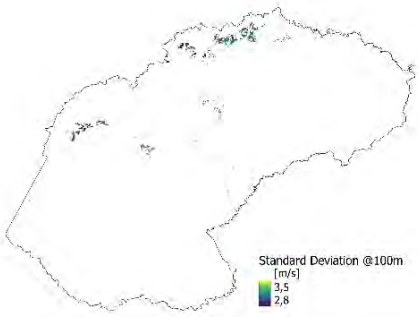


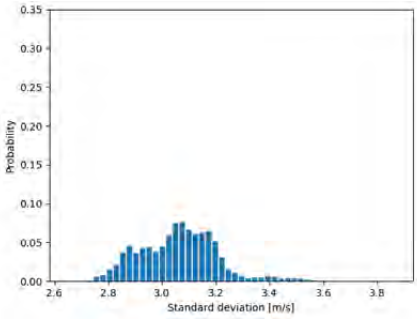




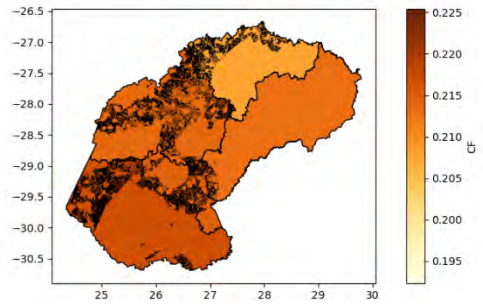


Volatility indicator (wind)

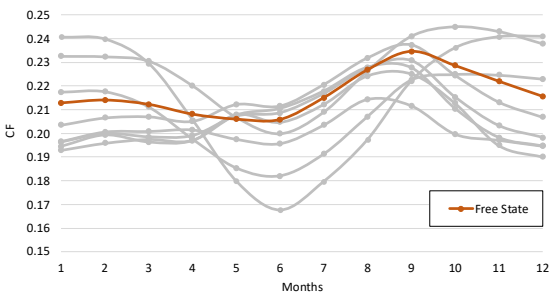




CF maps disaggregated by district municipalities (solar)
****orange colours as representative to the Admissible areas only***



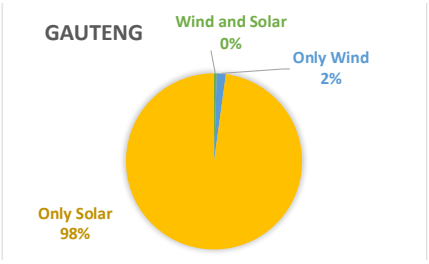
Volatility indicator (solar)



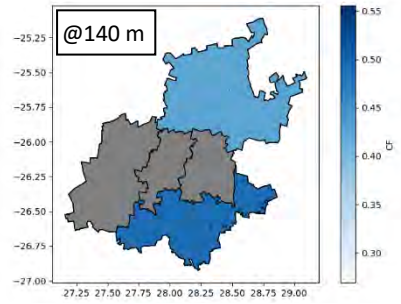
GAUTENG

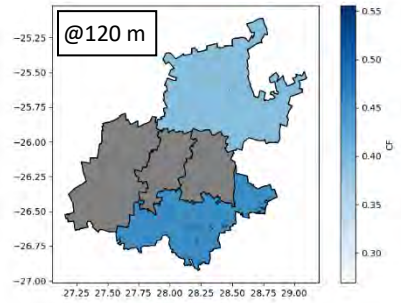
Summary Indicators	
Admissible area for V-RES:	2230 km^2 (12%)
Area exploitable by wind:	48 km^2 (0.3%)
Area exploitable by solar:	2193 km^2 (12%)
Average PV CF (Ⓢ)	0.21
Average Wind CF @90m (Ⓢ)	0.39
Average Wind CF @100m (Ⓢ)	0.41
Average Wind CF @120m (Ⓢ)	0.45
Average Wind CF @140m (Ⓢ)	0.48

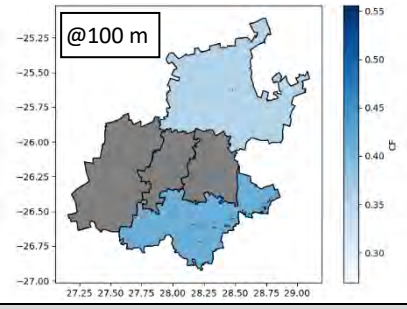
Pie chart

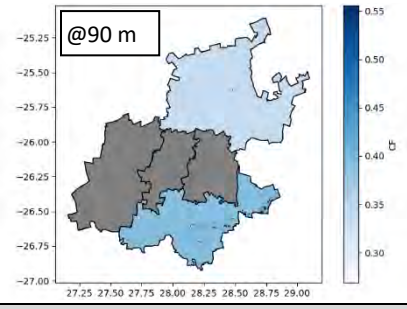


CF maps disaggregated by district municipalities (wind) ****blue colours as representative to the Admissible areas only***

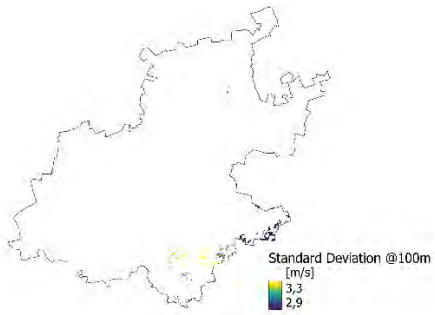


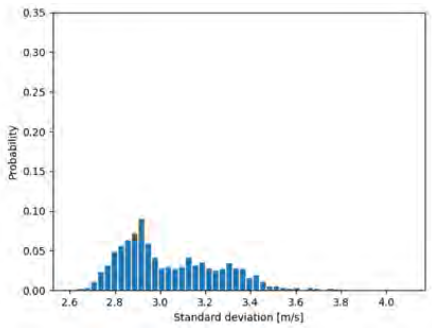




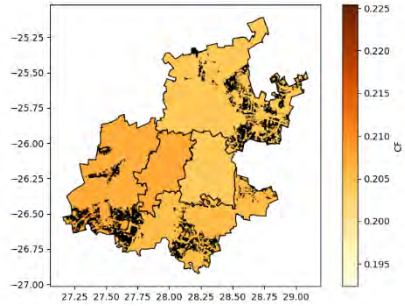


Volatility indicator (wind)

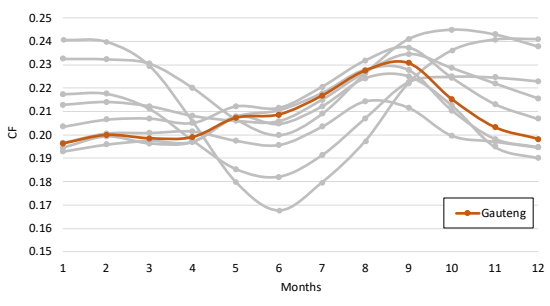




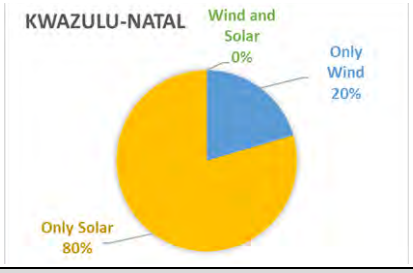
CF maps disaggregated by district municipalities (solar)
****orange colours as representative to the Admissible areas only***



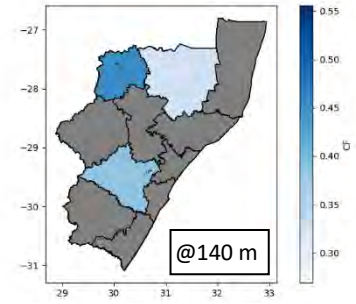
Volatility indicator (solar)

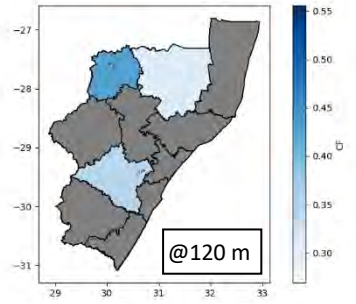


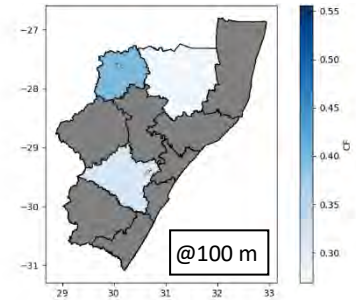
KWAZULU NATAL

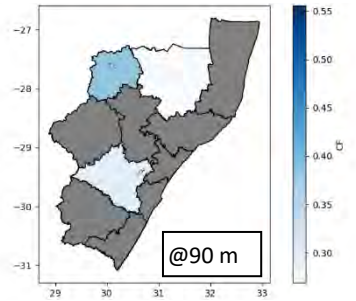
Summary Indicators		Pie chart
Admissible area for V-RES:	248 km^2 (0.3%)	
Area exploitable by wind:	51 km^2 (0.1%)	
Area exploitable by solar:	197 km^2 (0.2%)	
Average PV CF (Ⓢ)	0.20	
Average Wind CF @90m (Ⓢ)	0.33	
Average Wind CF @100m (Ⓢ)	0.35	
Average Wind CF @120m (Ⓢ)	0.38	
Average Wind CF @140m (Ⓢ)	0.41	

CF maps disaggregated by district municipalities (wind) ****blue colours as representative to the Admissible areas only***

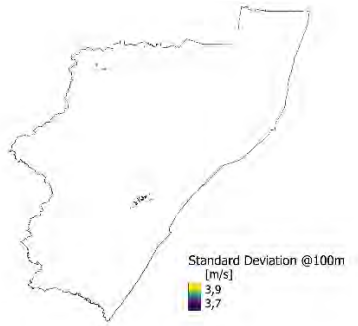


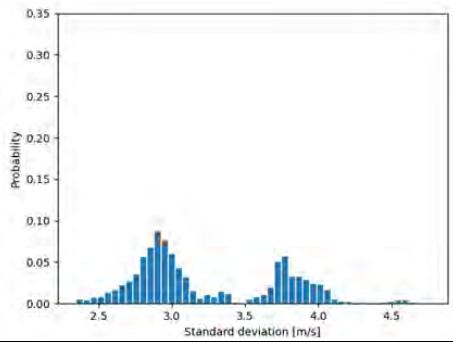




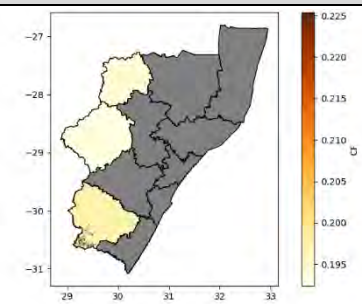


Volatility indicator (wind)

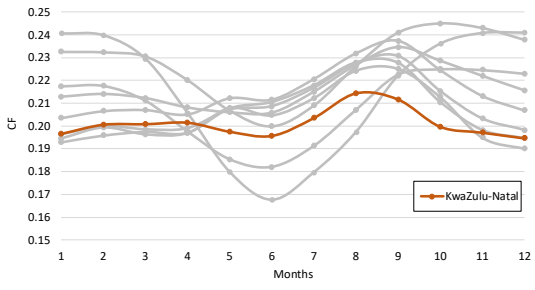




CF maps disaggregated by district municipalities (solar)
****orange colours as representative to the Admissible areas only***



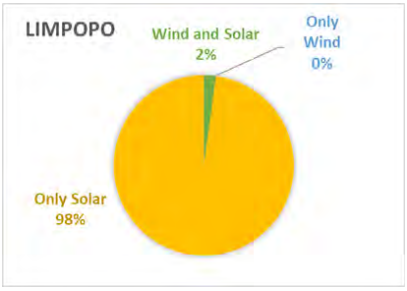
Volatility indicator (solar)



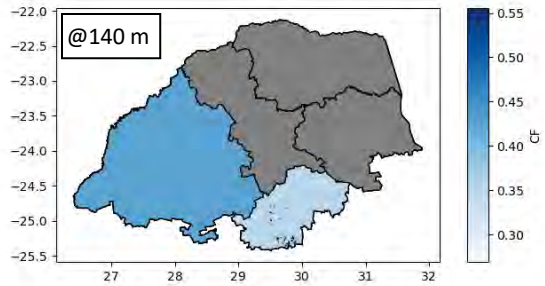
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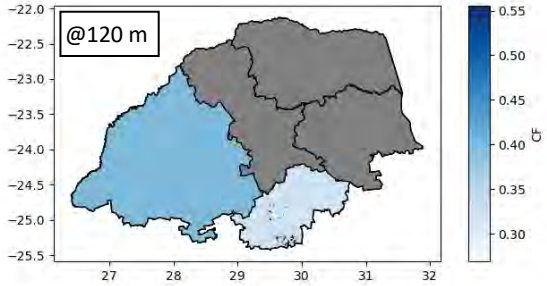
Summary Indicators	
Admissible area for V-RES:	8109 km^2 (6%)
Area exploitable by wind:	176 km^2 (0.1%)
Area exploitable by solar:	8109 km^2 (6%)
Average PV CF (Ⓢ)	0.20
Average Wind CF @90m (Ⓢ)	0.28
Average Wind CF @100m (Ⓢ)	0.29
Average Wind CF @120m (Ⓢ)	0.33
Average Wind CF @140m (Ⓢ)	0.35

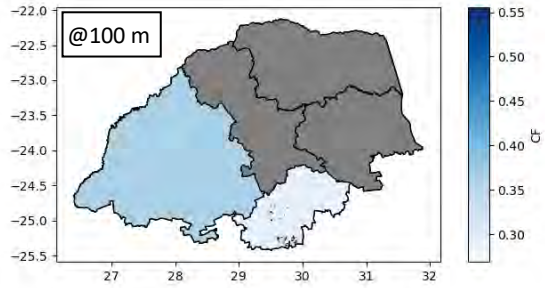
Pie chart

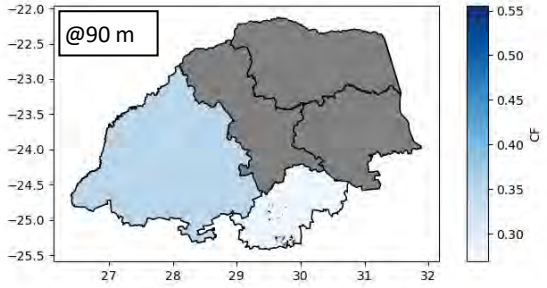


CF maps disaggregated by district municipalities (wind) ****blue colours as representative to the Admissible areas only***

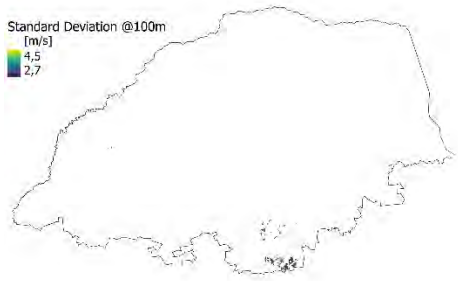


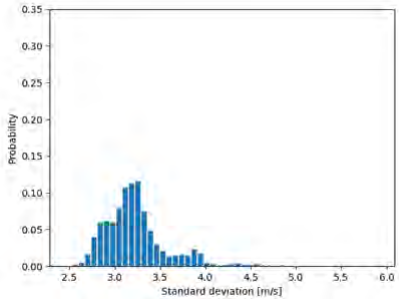




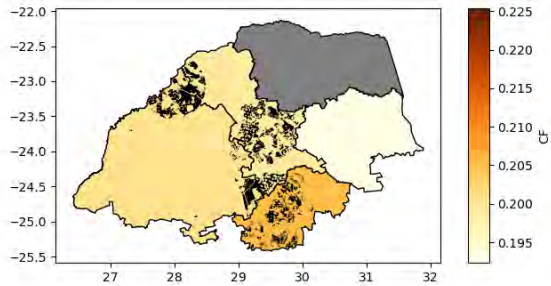


Volatility indicator (wind)

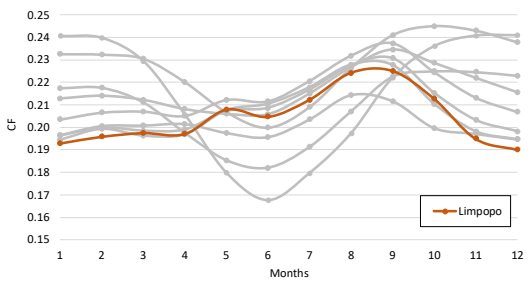




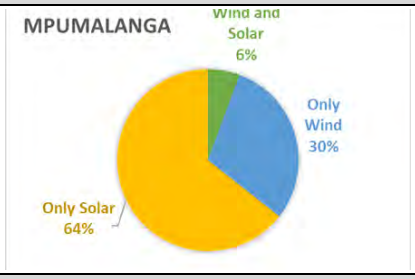
CF maps disaggregated by district municipalities (solar)
****orange colours as representative to the Admissible areas only***



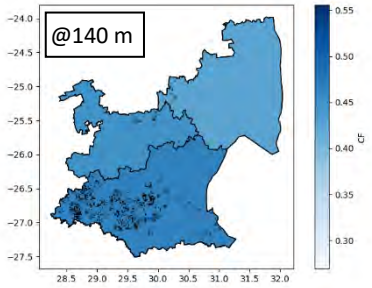
Volatility indicator (solar)

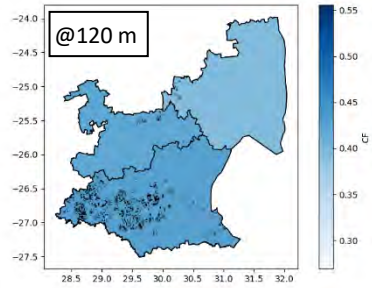


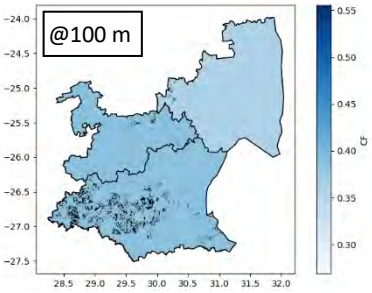
MPUMALANGA

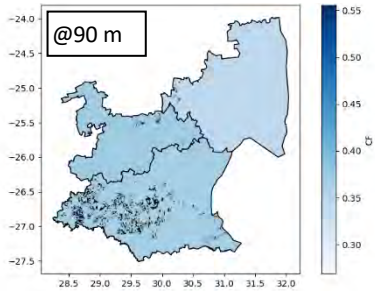
Summary Indicators		*Pie chart*
Admissible area for V-RES:	5677 km^2 (7%)	
Area exploitable by wind:	2021 km^2 (3%)	
Area exploitable by solar:	3977 km^2 (5%)	
Average PV CF (ⓢ)	0.20	
Average Wind CF @90m (ⓢ)	0.37	
Average Wind CF @100m (ⓢ)	0.39	
Average Wind CF @120m (ⓢ)	0.43	
Average Wind CF @140m (ⓢ)	0.46	

CF maps disaggregated by district municipalities (wind) ****blue colours as representative to the Admissible areas only***

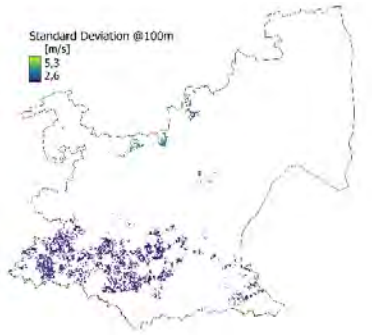


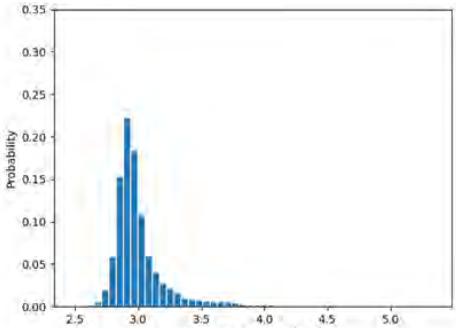




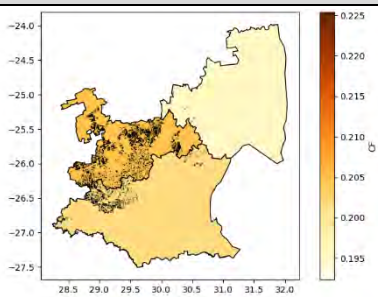


Volatility indicator (wind)

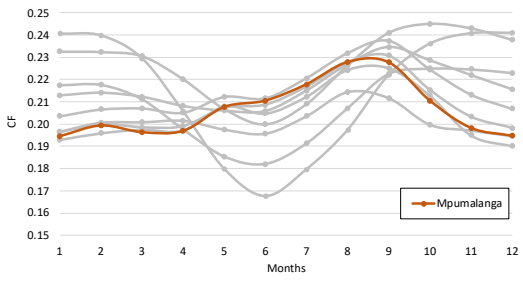




CF maps disaggregated by district municipalities (solar)
****orange colours as representative to the Admissible areas only***



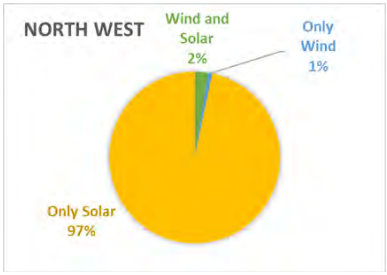
Volatility indicator (solar)



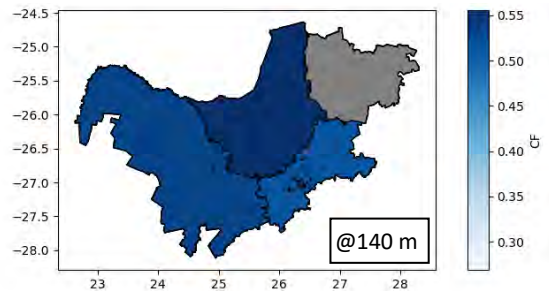
NORTH WEST

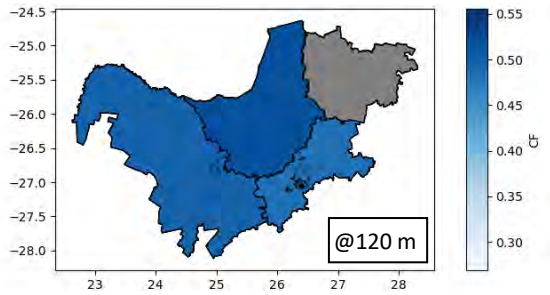
Summary Indicators	
Admissible area for V-RES:	18086 km^2 (17%)
Area exploitable by wind:	591 km^2 (1%)
Area exploitable by solar:	17948 km^2 (17%)
Average PV CF (Ⓢ)	0.21
Average Wind CF @90m (Ⓢ)	0.39
Average Wind CF @100m (Ⓢ)	0.43
Average Wind CF @120m (Ⓢ)	0.49
Average Wind CF @140m (Ⓢ)	0.52

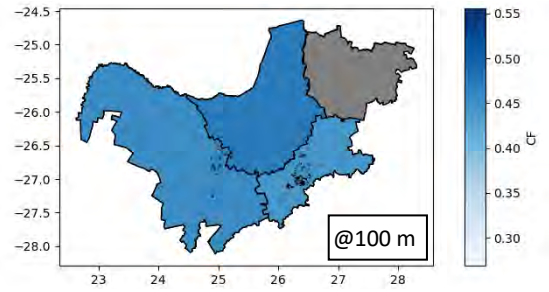
Pie chart

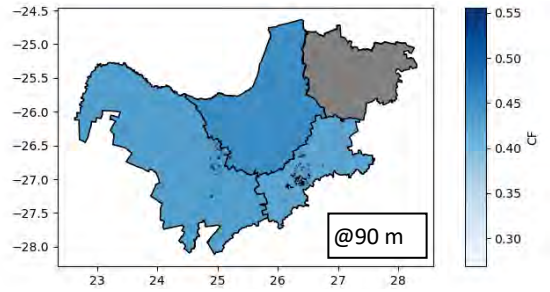


CF maps disaggregated by district municipalities (wind) ****blue colours as representative to the Admissible areas only***

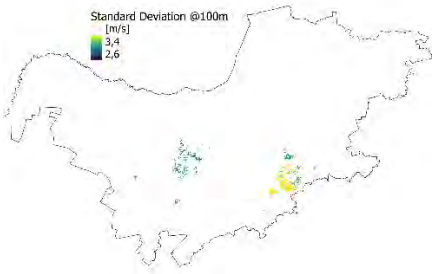


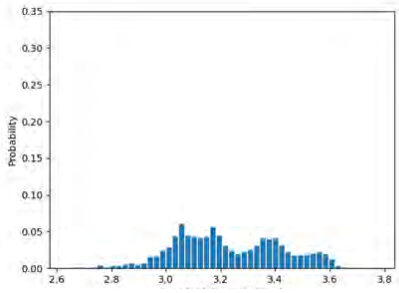




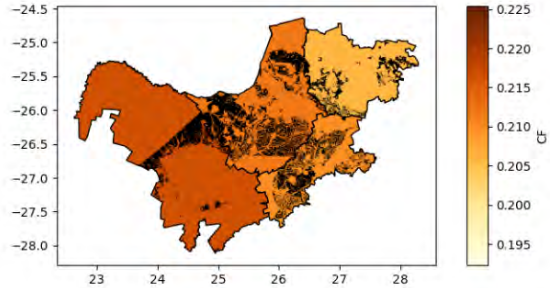


Volatility indicator (wind)

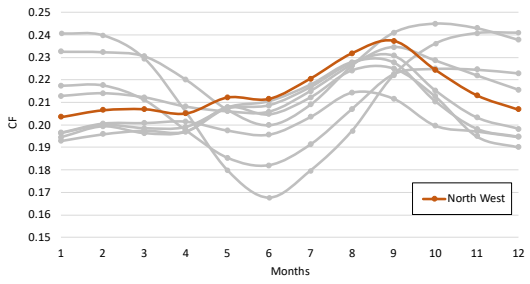




CF maps disaggregated by district municipalities (solar)
****orange colours as representative to the Admissible areas only***



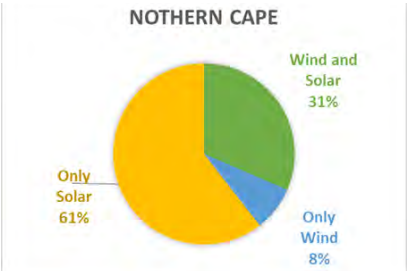
Volatility indicator (solar)



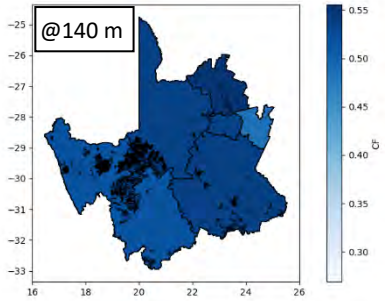
NORTHERN CAPE

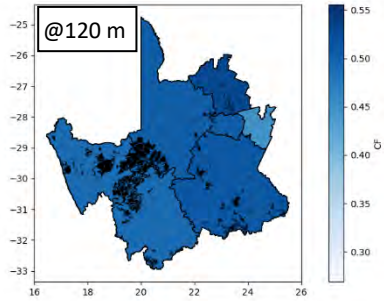
Summary Indicators	
Admissible area for V-RES:	75413 km^2 (20%)
Area exploitable by wind:	29766 km^2 (8%)
Area exploitable by solar:	69379 km^2 (19%)
Average PV CF (Ⓢ)	0.22
Average Wind CF @90m (Ⓢ)	0.44
Average Wind CF @100m (Ⓢ)	0.46
Average Wind CF @120m (Ⓢ)	0.50
Average Wind CF @140m (Ⓢ)	0.53

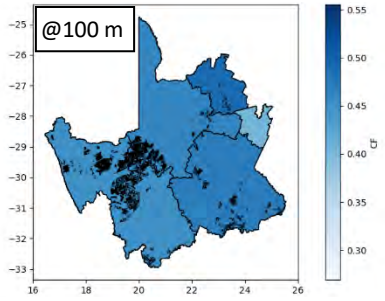
Pie chart

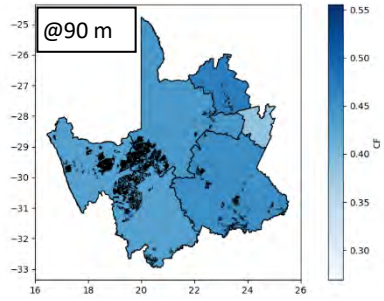


CF maps disaggregated by district municipalities (wind) ****blue colours as representative to the Admissible areas only***

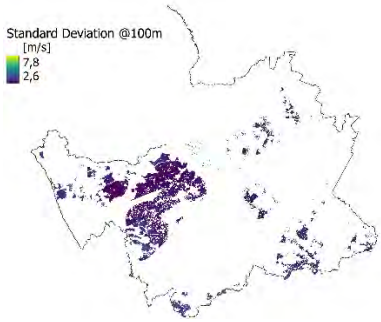


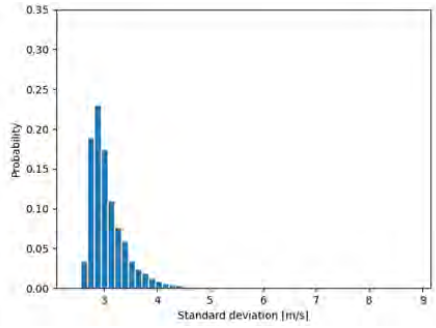




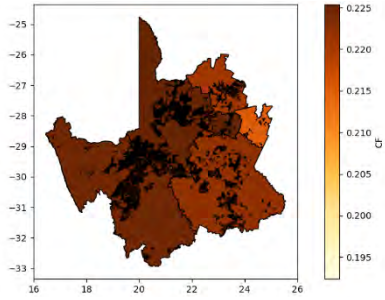


Volatility indicator (wind)

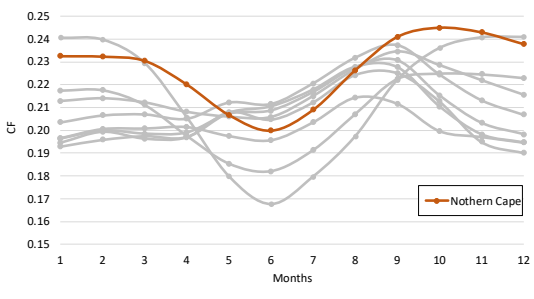




CF maps disaggregated by district municipalities (solar)
****orange colours as representative to the Admissible areas only***



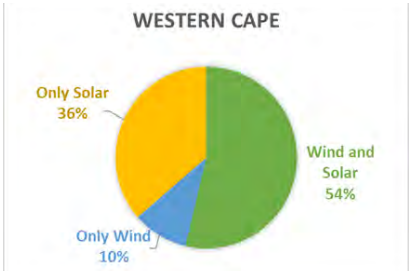
Volatility indicator (solar)



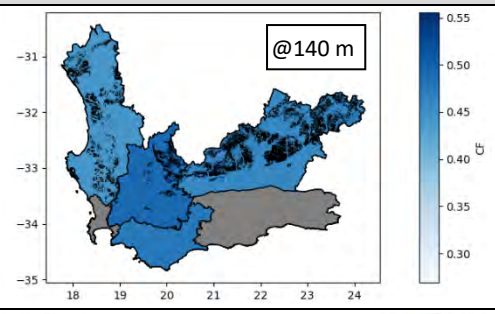
WESTERN CAPE

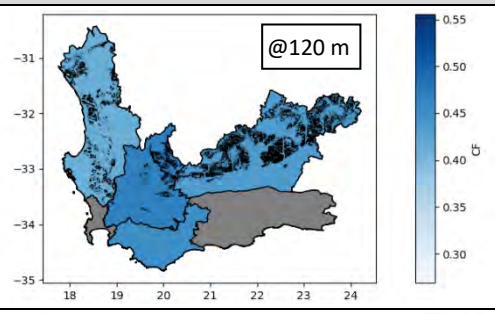
Summary Indicators	
Admissible area for V-RES:	26053 km^2 (20%)
Area exploitable by wind:	16580 km^2 (13%)
Area exploitable by solar:	23463 km^2 (18%)
Average PV CF (Ⓢ)	0.21
Average Wind CF @90m (Ⓢ)	0.39
Average Wind CF @100m (Ⓢ)	0.40
Average Wind CF @120m (Ⓢ)	0.43
Average Wind CF @140m (Ⓢ)	0.46

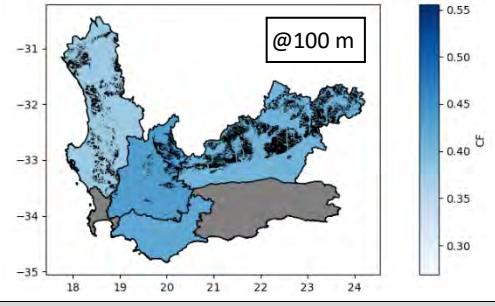
Pie chart

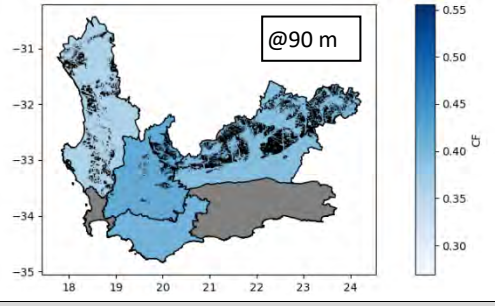


CF maps disaggregated by district municipalities (wind) ****blue colours as representative to the Admissible areas only***

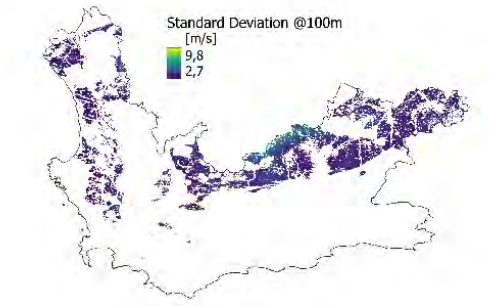


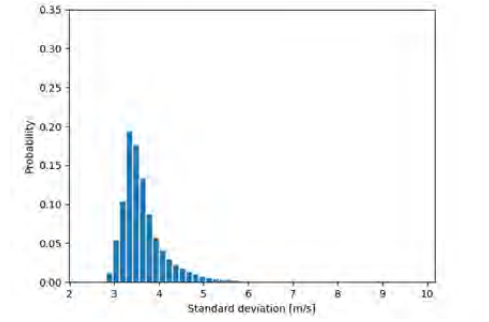




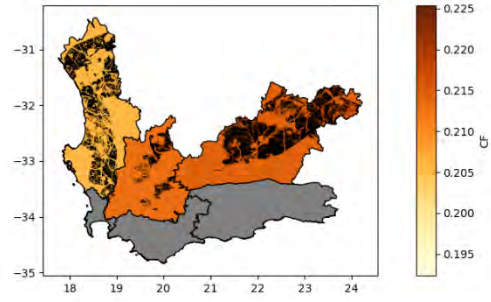


Volatility indicator (wind)

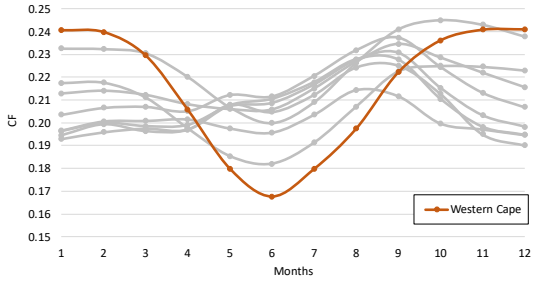




CF maps disaggregated by district municipalities (solar)
****orange colours as representative to the Admissible areas only***



Volatility indicator (solar)



6. STEP 4: CALCULATION OF V-RES KPIS

6.1 Goal

The goal of this step is to determine the Key Performance Indicators (KPIs) to evaluate the optimal integration of V-RESs in the areas where both wind and solar resources could be potentially exploited. The KPIs are meant to assess the following aspects:

4. Maximum capacity installable of wind and solar plants, namely "*KPI-Maximum Installable Capacity*".
5. Maximum energy producible, namely "*KPI-Yearly energy production".*
6. Cost of energy, namely "*KPI-LCOE".*

6.2 Procedure

The adopted procedure follows the steps described in detail in the following paragraphs aimed to collect the input data and process them in order to generate the desired output.

6.2.1 Input data processing

Data used in this step of the procedure are a combination of techno-economic assumptions useful to determine the performance of solar and wind power plants, and geospatial data derived in the previous Steps. The values are derived from the literature, and justification is provided. In other to test the impact of the most sensitive parameters on the results, some variables will be subject to sensitivity analysis in Section 8 and marked with the Ⓢ symbol. Table 3 shows the parameters that were determined for both wind and PV plants, in particular:

- *Land occupation* Ⓢ: it represents the amount of surface area that is expected to be occupied by wind and PV plants, considering the necessary spacing between modules and wind turbines. The latter, according to literature analysis and the SEA report, depends on the diameter (D) of the turbines, which should be oriented towards the wind: "7D" is the estimated distance between turbines along the direction facing the wind and "5D" is the distance on the orthogonal direction. As for PV plants, the value depends on local design considerations (e.g., vertical distance between the top of one row and the base of the next, hours of the day the rows must remain unshaded), which in turn depends on specificities of the local context (e.g., the latitude, morphology). Since the design of the plant is out of the scope of this analysis, an average value of space requirement is introduced, and set equal to 2.4 ha/MW. The value has been estimated by starting from the value of 2.5 ha/MW from SEA study (2015) and considering a 5% reduction attributed to efficiency improvement of today panels. The latest significant improvements in the efficiency of this technology is suggesting a further decrease of this parameter for solar PV.
- *CAPEX* Ⓢ: the total capital expenditure for PV and wind plants. For wind turbines, their cost has been estimated as function of hub height, according to the values of Table 4, taken from literature and the input provided by O&M working group in SAWEA. For PV plants, values from the literature have been adopted.
- *OPEX* Ⓢ: the yearly operating expenditure related to maintenance and operational costs as a fraction of the CAPEX at the different hub heights.
- *WACC*: it is the Weighted Average Cost of Capital.
- *Project Lifetime* Ⓢ: it is the expected useful life of a V-RES plant.

Table 3 Parameters of PV and Wind plants

Parameter	PV	Source	Wind	Source
Land occupation	2.4 ha/MW Ⓢ	SEA study [7] + CESI assumptions	5Dx7D	SEA study
CAPEX	800 $/kW Ⓢ	Lazard [8] (fixed tilt PV system Ⓢ)	Dependent on hub height Ⓢ	SAWEA + NREL [9]
OPEX	9.5 $/kW/year Ⓢ	Lazard [8] (fixed tilt PV system Ⓢ)	2.7% of CAPEX Ⓢ	Lazard [8]
WACC	0.096	Lazard [8]	0.096	Lazard [8]
Project Lifetime	30 years	Lazard [8]	20 years Ⓢ	Lazard [8]

Table 4 CAPEX of wind turbines as function of hub height Ⓢ.

Parameter	90m	100m	120m	140m	Source
CAPEX	1000 $/kW	1070 $/kW	1210 $/kW	1350 $/kW	SAWEA + NREL [9]

With respect to wind turbines, given the high variability of models and brands available on the market, with different characteristics, 4 different reference turbines are considered for deriving the related technical parameters (kept anonymous on purpose):

5) 1 IEC Class III turbine, with relatively "Small" power (4.7 MW).
6) 1 IEC Class I-II turbine, with relatively "Small" power (5 MW).
7) 1 IEC Class III turbine, with relatively "Big" power (6.6 MW).
8) 1 IEC Class I-II turbine, with relatively "Big" power (6.6 MW).

The selected nominal powers (4.7 MW, 5 MW, 6.6 MW) have been considered as representative of the possible future installations in South Africa, based on some considerations from the O&M working group in SAWEA.

Table 5 Reference turbine types

Turbine types				
Nominal Power	4.7	5	6.6	6.6
Turbine Diameter (D) [m]	155	145	170	155
	"Small"		"Big"	
Land occupation [ha/MW]	17.9	14.7	15.3	12.7
Wind Class	Class III	Class I-Class II	Class III	Class I-Class II

6.2.2 Methodology

The methodology of Step 4 is composed by several sub-steps, performed with geospatial analysis techniques, as shown in Figure 25.

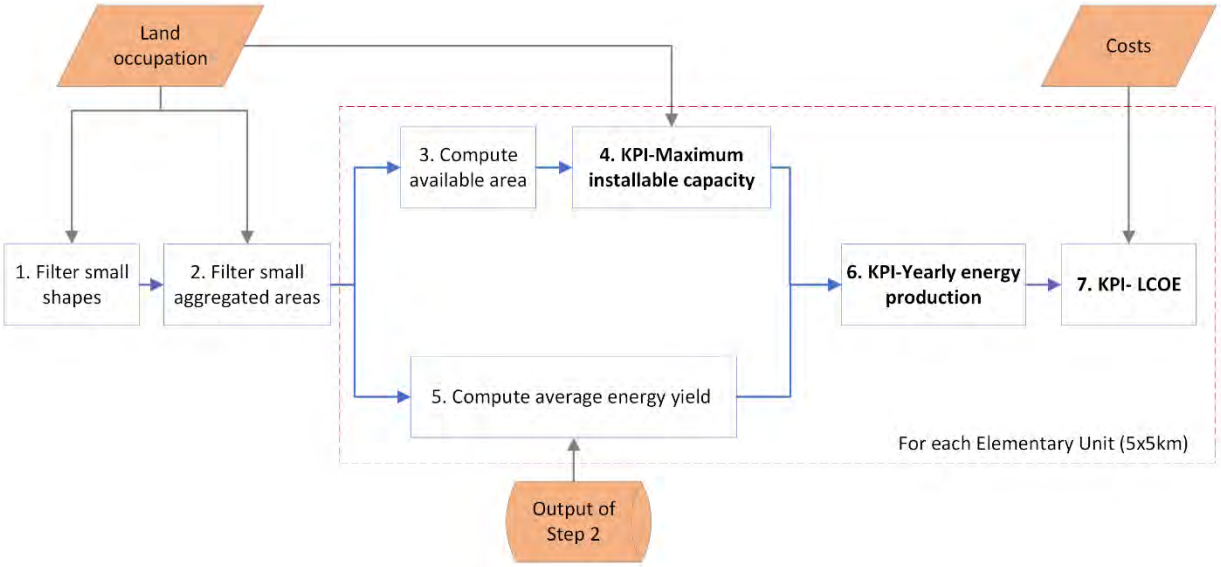


Figure 25 Flow chart of methodology of Step 4

For wind plants, the analysis is repeated for each class of turbine (reported in Table 5) and at each hub height under analysis (90m, 100m, 120m and 140m). At 90m hub height, only the "Small" turbines are considered, to keep a minimum clearance from the ground of 10 meters.

1. *Filter small shapes*: at first, the Admissible areas for PV and wind plants installations (taken from the layer *Admissible areas* described in Step 1) have been filtered to exclude polygons with a surface lower than a minimum threshold, probably a "noise" resulted in the analysis geospatial analysis performed in the SEA (Figure 26). To exclude these areas, the following assumption has been introduced: in case of PV modules, all the polygons with an area that could host less than 1MW of farm area are excluded, while for wind, all the polygons with an area that could accommodate less than one (1) turbine with necessary spacing are excluded.

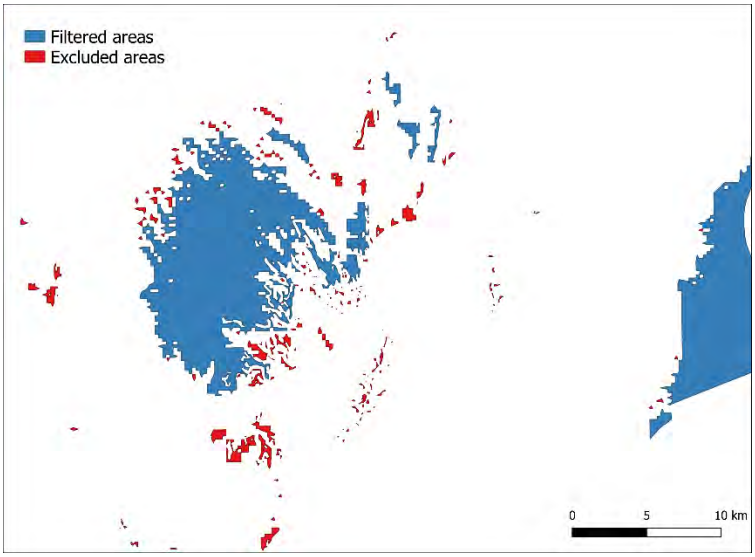


Figure 26. Example of small shapes/noises that have been excluded.

2. *Filter small, aggregated areas*: being the scope of the analysis the integration of VRES at the transmission level, areas have been further filtered to consider a minimum capacity of PV and wind farms that would "justify" an eventual investment on the grid side (e.g., planning, extension, new substations). This value has been set, according to input provided by Eskom, at 100 MW for PV and 250MW for wind. Operationally speaking (Figure 27), pixels composing the *Admissible areas* have been buffered with a radius of 2.5 km, so to merge all the areas with distance lower than 5km and compute their surface. 5 km is in fact considered a reasonable length for MV lines which could interconnect turbines or PV modules inside the same farm, that can eventually be connected at the transmission grid. The aggregated areas that do not respect the minimum threshold have been discarded.

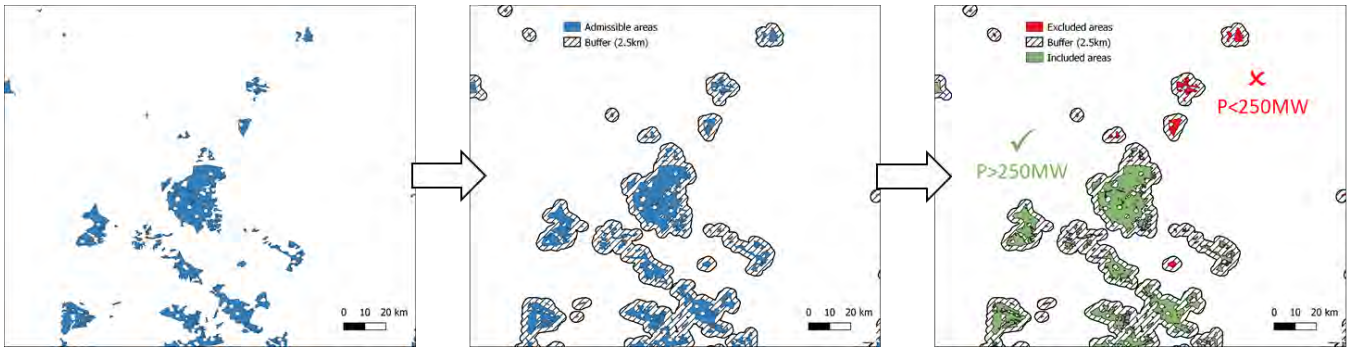


Figure 27. Graphical representation for evaluating the considered aggregated areas.

3. *Compute available area*: empty regular grid of polygons is created, with resolution of each pixel of around 5km x 5km, as requested by Eskom. Each pixel of this grid is called an "Elementary Unit". For each Elementary Unit, the available filtered surface area for PV and wind plants is computed.
4. *KPI-Maximum Installable Capacity*: from the available filtered surface area for PV and wind plants in each pixel, the KPI-Maximum Installable Capacity is calculated for each Elementary through the land occupation parameter introduced in Table 3.
5. *Compute the average energy yield*: intersecting the output of the Solar and Wind Atlases derived in Step 2, with the grid of polygons calculated before, the average energy yield for each Elementary Unit is computed.
6. *KPI-Yearly energy production (E_i)*: the average yearly energy production [MWh/year] is computed for each Elementary Unit multiplying the energy yield [MWh/MW] with the *KPI-Maximum Installable Capacity* [MW].
7. *KPI-LCOE*: the Levelized Cost of Energy is computed considering the following formula, based on a discounted cash flow method. Among the cash flows, taxation, subsidies, and other incentives are not considered to avoid increasing the complexity.

$$\mathrm{LCOE} = \frac{\sum_{i=1}^{lifetime} \frac{\mathrm{CAPEX} + \mathrm{OPEX_i}}{(1+WACC)^i}}{\sum_{i=1}^{lifetime} \frac{E_i}{(1+WACC)^i}}$$

6.2.3 Output

The outputs of the Step 4 are delivered as follows:

1. *Solar LCOE-Capacity-Energy Atlas*: one (1) vector file (.shp format) composed by Elementary Units with associated the average *KPI-LCOE* [$/MWh] (attribute "LCOE"), the associated potential *KPI-Maximum Installable Capacity* [MW] (attribute "P [MW]"), and the expected *KPI-Yearly energy production* [MWh/year] (attribute "E [MWh]") of solar PV.
2. *Wind LCOE-Capacity-Yield Atlas*: seven (7) vector files (.shp format) composed by Elementary Units with associated the average *KPI-LCOE* [$/MWh] (attribute "LCOE"), the associated potential *KPI-Maximum Installable Capacity* [MW] (attribute "P [MW]"), the expected *KPI-Yearly energy production* [MWh/year] (attribute "E [MWh]") of wind, and the IEC class at the four different hub heights and for the "Small" and "Big" reference turbines.

6.3 Results and discussion

The results of the simulations are provided as polygon vector files, composed by Elementary Units, with attributes related to the three computed KPIs: *KPI-Maximum Installable Capacity, KPI-Yearly energy production* and *KPI-LCOE.*

The overall results related to solar PV plants are shown in Table 6, where the maps are coloured according to the KPIs values, with darker colours corresponding to higher values. Reflecting the results of Step3, the areas with highest energy production, highest installable capacity and lowest LCOE are the north-western areas of Northern Cape province.

Table 7, Table 8, and Table 9 show and discuss the results related to wind power plants at a hub height of 100 m.

Table 6 Results on KPIs for solar PV.

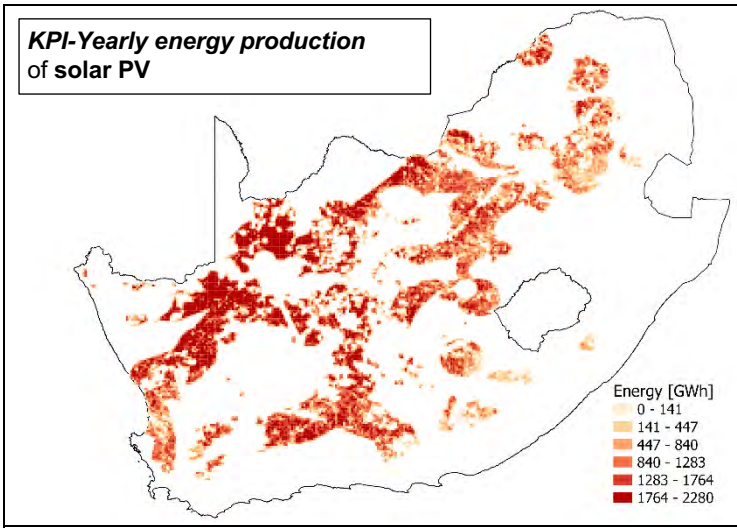
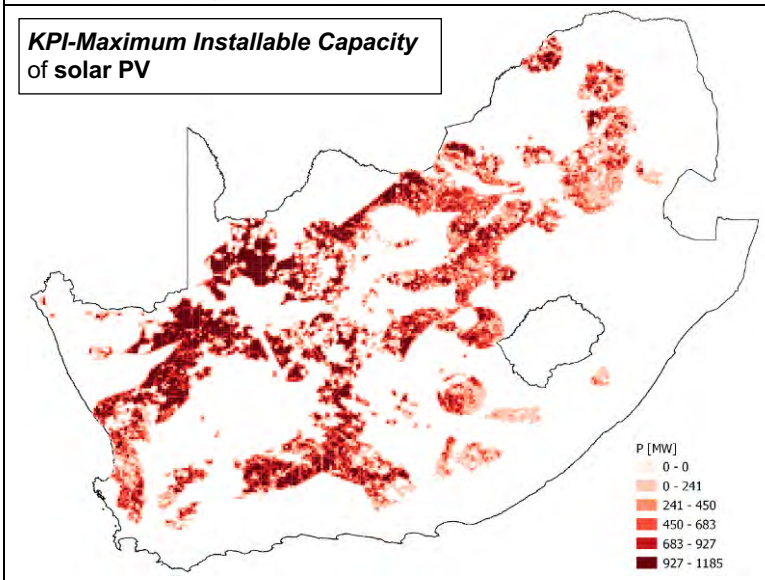
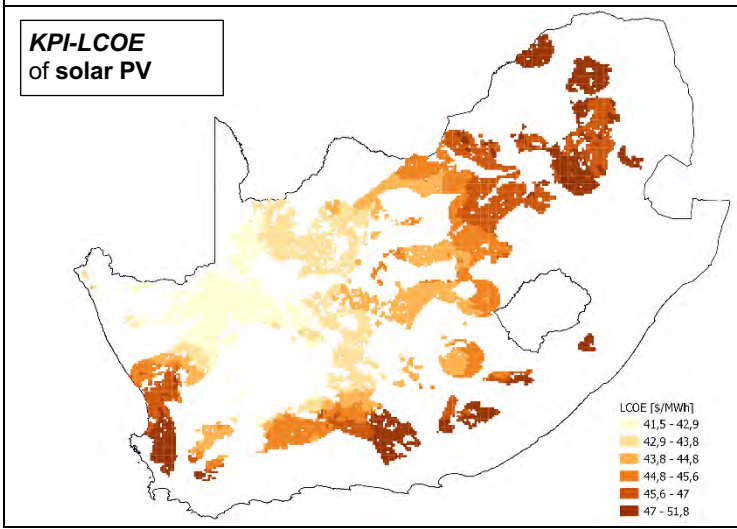
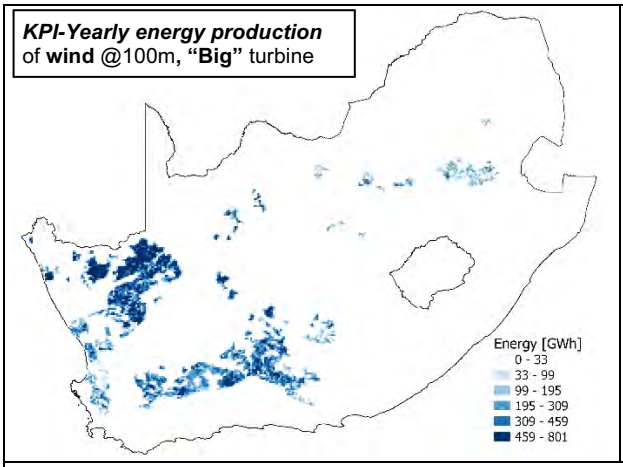
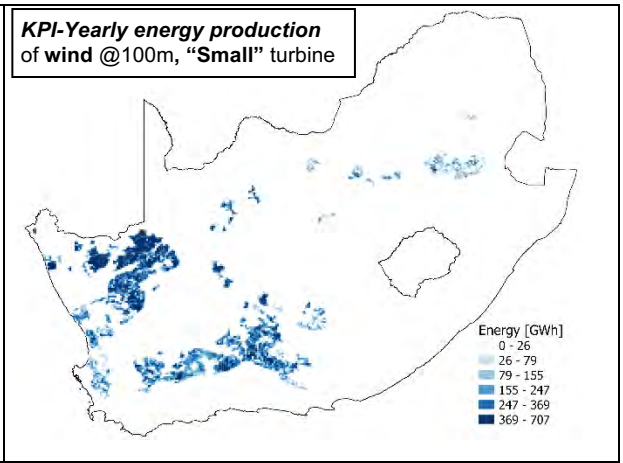
KPI-Yearly energy production of **solar PV** 	The map confirms the expected high yearly energy of solar PV, reaching up to 2200 GWh per year per Elementary Unit (5x5 km) in Northern Cape. This map is subject to sensitivity analysis in Section 8 (Ⓢ).
KPI-Maximum Installable Capacity of **solar PV** 	In terms of installable capacity per Elementary Unit, results reach very high values in most the country, with the Admissible Areas in Northern Cape that exceed 1 GW of installable capacity. This is the result of the fact that Northern Cape, besides being the Province with the highest solar potential, is also the Province where the Admissible Areas are more contiguous and less scattered, and so more suitable for the installation of bigger PV farms. This map is subject to sensitivity analysis in Section 8 (Ⓢ).
KPI-LCOE of **solar PV** 	The LCOE map has a opposite trend of energy production map. The areas with the highest energy production are those with the lowest LCOE, installable capacity being equal. This leads the LCOE of Northern Cape areas to be lower than 43 $/MWh while some areas in the northeast of the country to approach 50 $/MWh. This map is subject to sensitivity analysis in Section 8 (Ⓢ).

Table 7 Results on KPI-Yearly energy production for wind @100m.

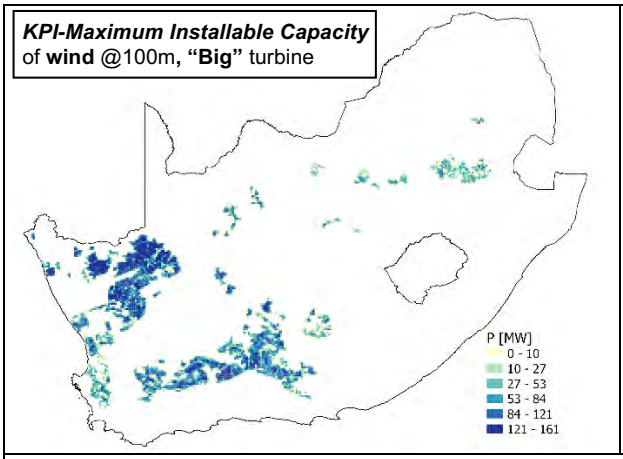


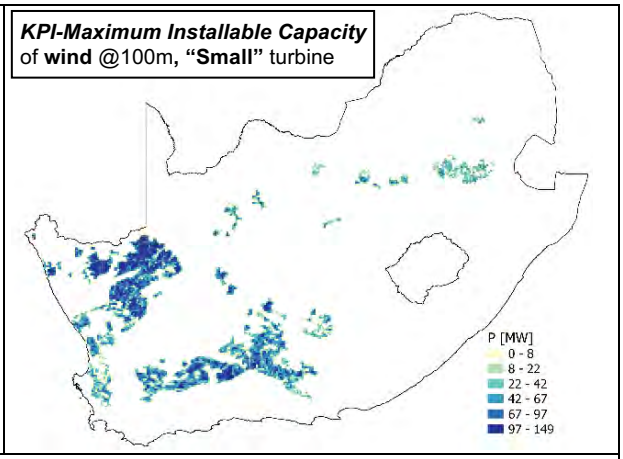


The map confirms the expected high yearly energy producible from for wind resource in the Eastern and Northern Capes, ranging in most of the Admissible areas between 460 GWh and 800 GWh ("Big" turbines) and 370 GWh and 700 GWh ("Small" turbines) per Elementary Unit (5x5 km). Lower values for "Small" turbines are lower due to the fact that "Big" turbines allow to produce more energy per unit of surface occupied area (see discussion on next KPI).

The "Small" turbine map is subject to sensitivity analysis in Section 8 (Ⓢ).

Table 8 Results on KPI- Maximum Installable Capacity for wind @100m.



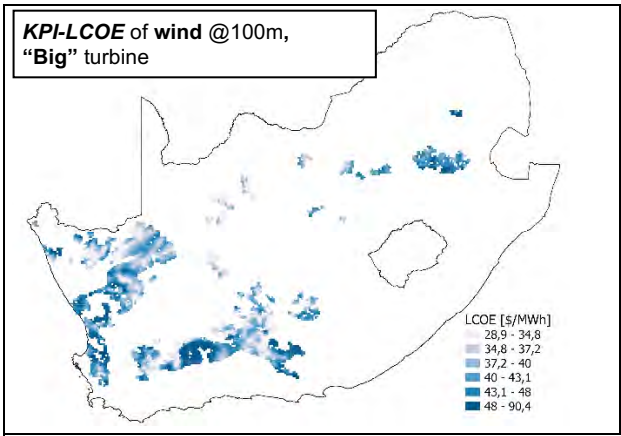
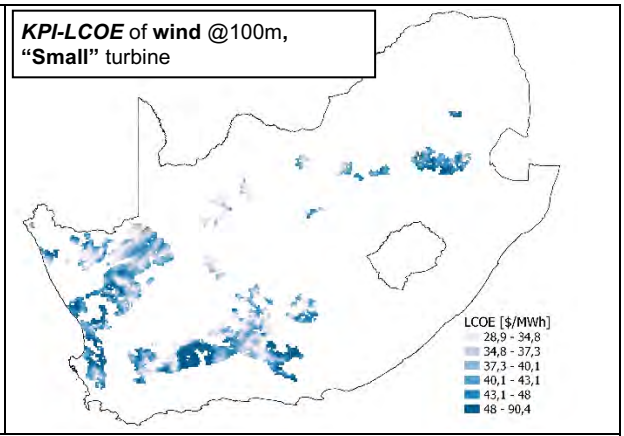


In terms of installable capacity per Elementary Unit, results reach higher values in Northern and Eastern Capes, exceeding 110 MW ("Big" turbines) and 90 MW ("Small" turbines) of installable capacity per Admissible Area. The lower installable capacity for "Small" areas is the results of two facts:

1) As per Table 5, the diameter (and therefore the occupied land) of "Big" turbines increases less proportionally than the increase of their nominal power with respect to the "Small" turbines.
2) Having a higher nominal power per unit of occupied land, "Big" turbines are less subject to the filtering phase of aggregated areas (see Figure 27), since they meet more easily the minimum threshold of 250MW respect to the "Small" turbines. This effect offset the opposite one related to the filtering phase of small shapes (see Figure 26), which favours the "Small" turbines.

The "Small" turbine map is subject to sensitivity analysis in Section 8 (Ⓢ).

Table 9 Results on KPI- LCOE for wind @100m.

	
Also for wind, the KPI-LCOE reflects the fact the areas with the highest energy production are those with the lowest LCOE, installable capacity being equal. This leads the LCOE to range between 29 $/MWh in the areas with the highest potential, to 90 $/MWh in the less favourable areas of the country. The effect KPI is not affected by the type of turbine because, based on the hypothesis described in paragraph 6.2.1, the specific values of CAPEX and OPEX [i.e., $/kW] are only function of the hub height, and so the advantages of "Big" turbines on the previous two KPIs, as described above, are offset in the LCOE formula (reported in Section 6.2.2). The "Small" turbine map is subject to sensitivity analysis in Section 8 (Ⓢ).	

The next analysis focuses on the LCOE values for solar and PV. Figure 28 shows the LCOE resulting from the simulations in each Elementary Unit, for both solar PV and wind technologies. It is plotted as a function of the energy yield to show the strong correlation between the availability of the primary energy source and the LCOE: at high energy yields (i.e., high CF), the availability of RES is higher and the cost per unit of production decreases, given the possibility of better exploiting the installed capacity. Also, to highlight the distribution of the two variables on the axes (i.e., LCOE and energy yield), the related *boxplots* are represented in order to show the distribution of data into quartiles, highlighting the median and outliers. The results show that, since solar PV plants have a more homogeneous energy yield across the country, this leads to less variable solar LCOE values when compared to wind plants: LCOE ranges from around 50 $/kWh to around 40 $/kWh for PV plants against a range of 90 $/kWh to 30 $/kWh in the case of wind plants. In case of wind, the LCOE increases with the hub height of the turbines, showing that the higher energy production exploitable at higher altitudes does not necessary compensate the higher costs faced for the installation of taller turbines. This is of course the direct result of two factors:

1) The level of complexity in the formulation of the specific CAPEX and OPEX [i.e., $/kW] of wind turbines. In this study, the introduced degree of complexity has been a direct consequence of the available information. In fact, the cost of energy conversion technologies is usually a very highly sensitive information, that does not allow to derive disaggregated values per component (e.g., basement, pole, blades, engines, …) and therefore to a more discrete modelling of the CAPEX and OPEX. This is the reason why the representation of the specific CAPEX and OPEX [i.e., $/kW] as a function of the hub height, based on the available information derived from the literature [9], has been considered an already satisfactory level of approximation for the scope of this study.
2) The distribution of wind resource as altitude varies. This depends on the nature of the resource, that was an input of this study (see Step 1), and therefore not subject to discretionary assumptions.

Another useful consideration to properly discuss the results from Figure 28 is worth to be reported, as discussed with RES4Africa: developers are experiencing a trend in the V-RES LCOEs, which is favouring solar PV against wind. Among the possible reasons, developers are attributing this trend to the fact that wind sites are requiring longer and more expensive interconnections on average, considering also that the capacity of the REIPPP projects has been increased to 240 MW/site. Also, it is important to consider that this analysis consider fixed PV, whose LCOE is higher than PV with bifacial modules combined with tracking system, which is a technology that is penetrating fast in the V-RES South African market. The performances of PV with bifacial modules combined with tracking system have been tested in the sensitivity analysis (Ⓢ) in Section 8, and approximatively represented in Figure 28. Also, a less optimistic energy yield for wind is subject to sensitivity analysis (Ⓢ) in Section 8.

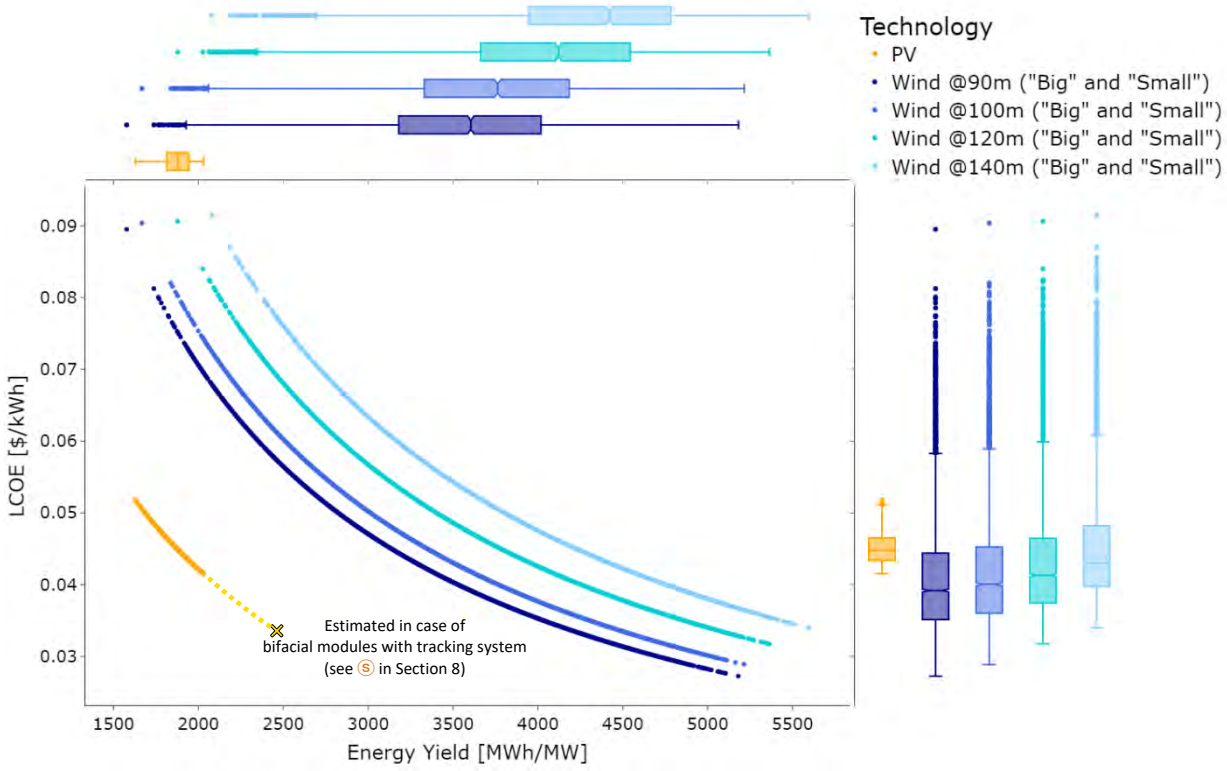
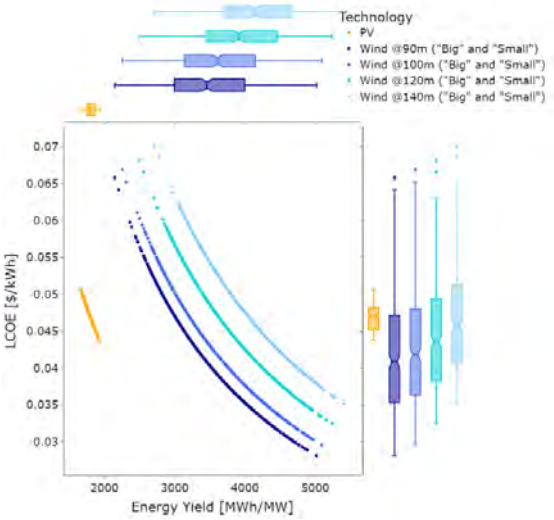


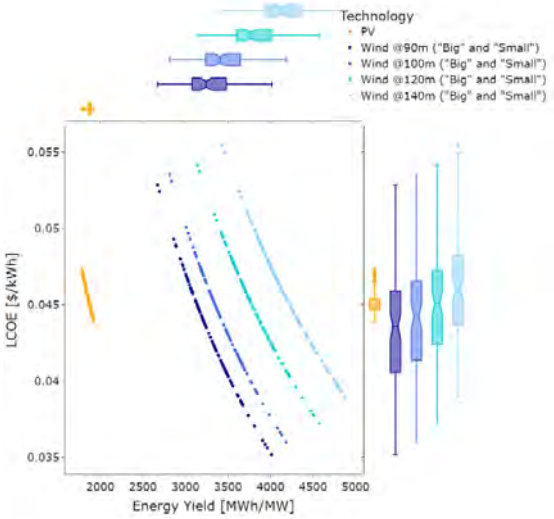
Figure 28 LCOE vs Energy Yield of PV and wind power plants. This graph is subject to sensitivity analysis in Section 8 (Ⓢ).

In addition, given the large range of LCOE for wind, the figures below report the same graph on LCOE vs Energy Yield of PV and wind power plants disaggregated by Provinces.

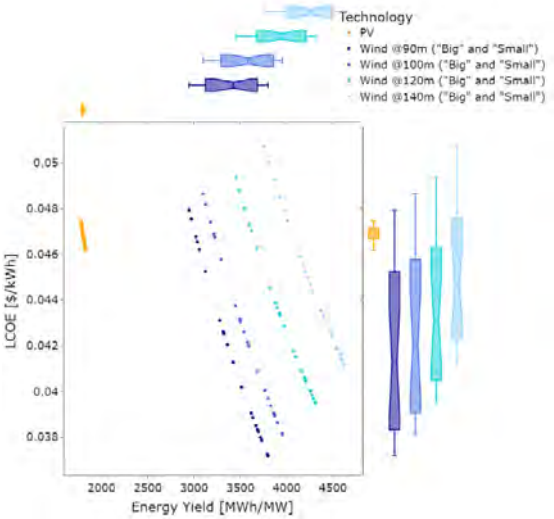
Eastern Cape



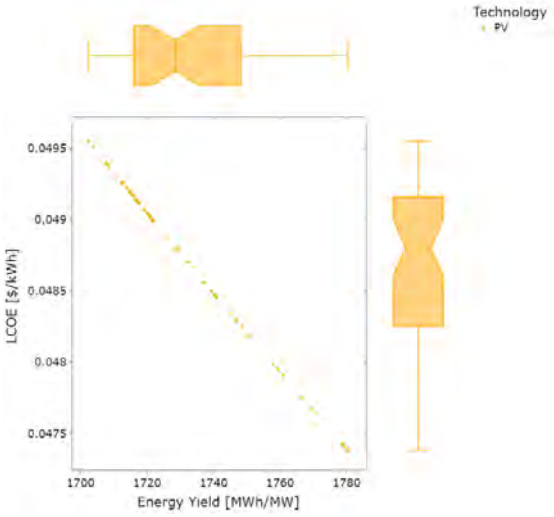
Free State



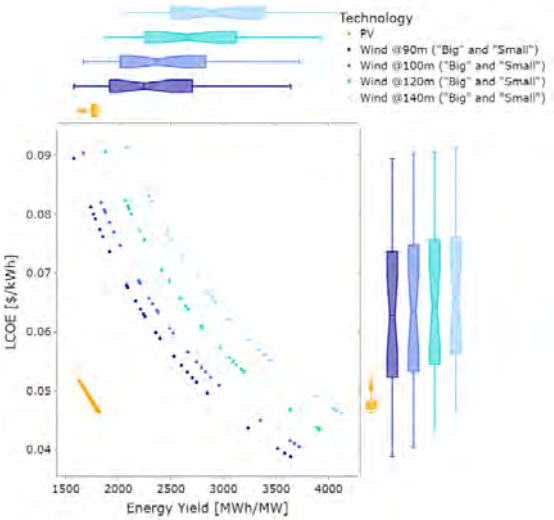
Gauteng



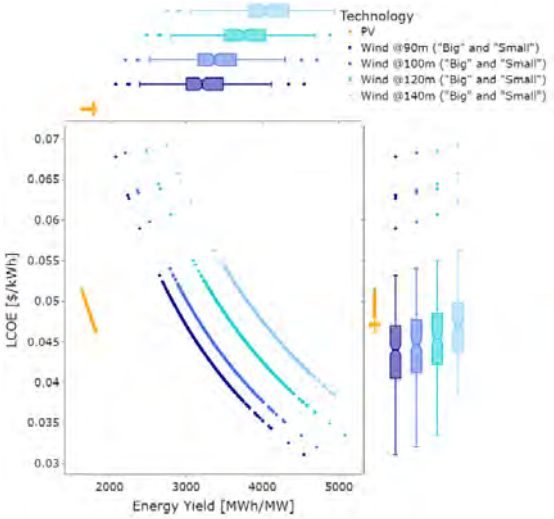
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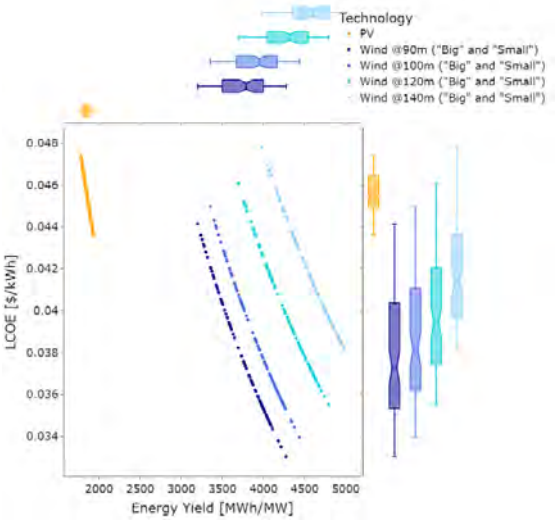
Limpopo



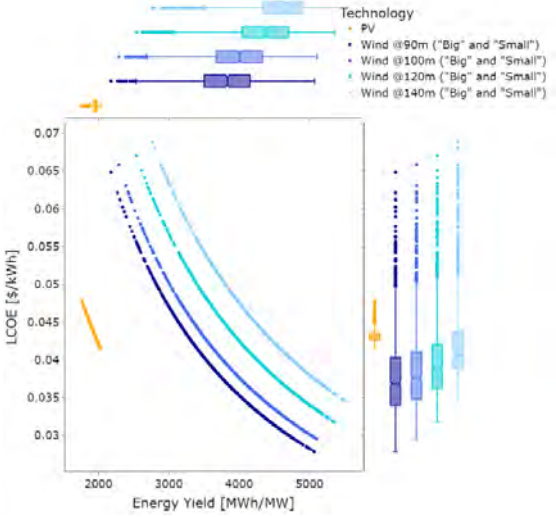
Mpumalanga



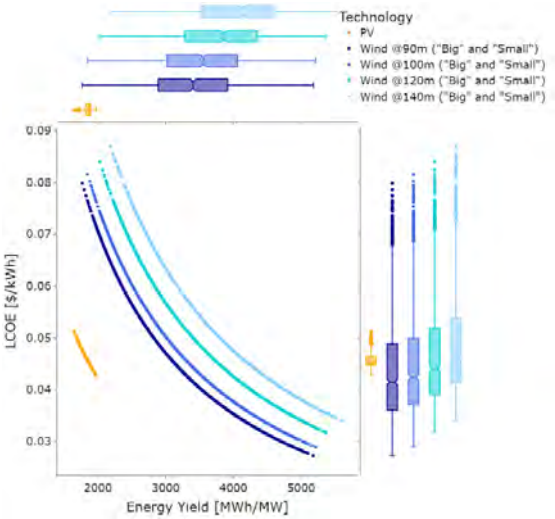
North West



Northern Cape



Western Cape



To contextualize the obtained results on LCOE, they are compared with LCOE values taken from literature and with the bid prices of the South African Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) (see Figure 29 and Figure 30). More in detail, the legend of the figure refers to:

- *Results*: LCOE values in the Elementary Units obtained with the simulations for PV and wind plants. They are represented in *boxplots* that shows the distribution of data into quartiles, highlighting the mean and outliers.
- *Lazard*: it is the *range* of LCOE values reported in *Lazard's levelized cost of energy analysis—version 15.0* [8]. For solar PV, the values correspond to Crystalline Utility Scale plants, with the lower value representing a single-axis tracking system and the higher value a fixed-tilt system.
- *IRENA*: *range and mean* of LCOE values reported in *IRENA-Power Generation Costs in 2020* [10]. The range of solar PV plants is calculated by IRENA as the 5th and 95th percentile of projects installed in 2020 across the World. The range of wind plants is the 5th and 95th percentile of projects installed in 2020 in Africa.

- REIPPPP BidW4: the *boxplots* show the values of bid prices of the winning projects in REIPPPP Bidding Window 4. The price is the fully indexed price (ZAR/MWh) converted in USD/kWh with the average exchange rate of 2014 (0.0923 USD/ZAR). For sake of simplicity, prices have not been corrected with the inflation rate.
- REIPPPP BidW5: the *boxplots* show the values of bid prices of the winning projects in REIPPPP Bidding Window 5. The price is the fully indexed price (ZAR/MWh) converted in USD/kWh with the average exchange rate of 2021 (0.0677 USD/ZAR). For sake of simplicity, prices have not been corrected with the inflation rate.

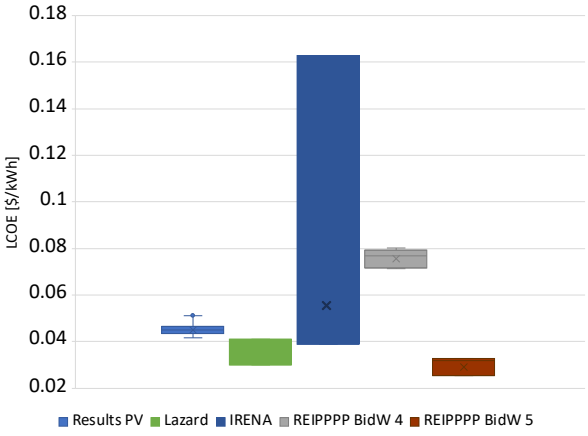


Figure 29 Comparison of LCOE results for PV plants with literature values and REIPPPP bid prices

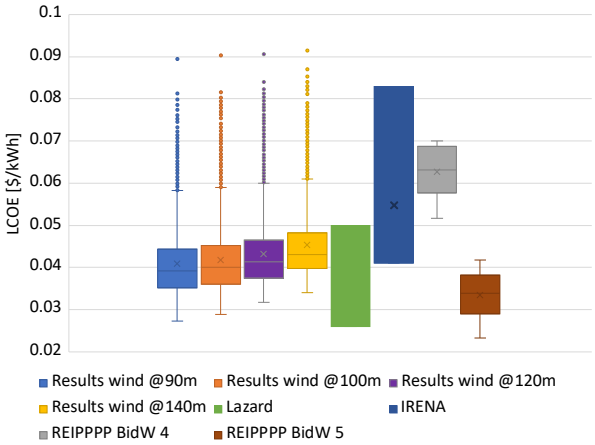


Figure 30 Comparison of LCOE results for Wind plants with literature values and REIPPPP bid prices

LCOE values obtained in the analysis are positioned in the higher range of LCOE values from Lazard and in the lower band of values from IRENA, hence in line with literature values.

Concerning the comparison with the REIPPPP prices, the LCOE for both wind and solar are lower than the BidW4 (2014) results, but higher than the latest BidW5 (2021), whose results are almost halved respect to 2014. Other than technical (e.g., fixed PV vs solar PV with tracking), the reasons behind the misalignment between simulation results and BidW5 prices may be manifold and mainly financial, as reported by IRENA in their comparison between Middle East bidding prices and the average literature LCOE [10]: boundary conditions may not match, while the full contract details are not available, meaning there could be additional payments or opportunities to raise revenue beyond the headline PPA price. Some factors reported by IRENA that may be extended also for explain the lower BidW5 results respect to the results of this study are:

- *Economies of scale*: considering that projects have larger sizes of 75MW (solar project) and 140MW (wind projects), the ability of project developers to secure the most competitive prices possible for services and hardware should not be underestimated.
- *Competitive O&M structures*: O&M costs considered by project developers may have been estimated in order to match the competitive values seen all over the world, given the increasing use of large amounts of data for preventative O&M, the use of drones for inspection and automated cleaning.
- *Low interest rate*: financing costs considered by project developers may be lower than what estimated in the study, given the fact that the off-taker, being government owned, are also at lower risk of default. This will reduce financing costs.

- *Consortiums including large multi-nationals*: the possible presence of multi-nationals among the bidders lead to other financial considerations, such as the fact that these entities have extremely strong quality assurance processes, access to a wealth of experience and strong balance sheets. The presence of module manufacturers will also potentially help reduce equipment costs.

Last, but not least, it cannot be excluded that such lower bids may be the results of strategic corporate considerations of the bidders for positioning in the South African IPPs electricity market.

7. STEP 5: OPTIMIZATION OF V-RES INTEGRATION

7.1 Goal

Most of the Admissible areas represent zones where both solar and wind can be potentially exploited. So far, the analysis kept separate the solar and wind Atlases, in order to analyse the potential of each V-RES independently. The goal of Step 5 of the procedure is to provide a single integrated solar and wind Atlas, by identifying the optimal integrated mix of V-RES for each Elementary Unit (5x5 km^2).

7.2 Procedure

7.2.1 Optimization process

In order to optimally allocate the two V-RES in the Elementary Units where both solar and wind may be installed, three (3) potential different alternative logics have been considered:

- *Power optimization*: in this case, in each Elementary Unit of the overlapped Solar LCOE-Capacity-Yield Atlas and Wind LCOE-Capacity-Yield Atlas created in Step 4 where both wind and solar resources are exploitable, the V-RES with the highest *KPI-Maximum Installable Capacity* [MW] is selected.
- *Energy optimization*: in this case, in each Elementary Unit of the overlapped Atlases, the V-RES with highest *KPI-Yearly energy production* [MWh/year] is selected.
- *Economic optimization*: in this case, in each Elementary Unit of the overlapped Atlases, the wind turbine with lowest LCOE (chosen among the different heights and IEC Class) is compared against solar, and the V-RES with lowest *KPI-LCOE* [$/MWh] is selected.

For each optimization logic, an optimization run is computed for Elementary Unit, allowing to allocate for each cell the V-RES that satisfies the optimization criterion adopted. The type of output is explained in the paragraph below, while the results are discussed in Section 7.3

It is worth to note that the optimization performed through the KPI-Maximum Installable Capacity and the KPI-Yearly energy production does not take into account the benefits exploitable from the local integration of different V-RES, as explained in Section 5.2.1 and demonstrated in the case-study included therein.

7.2.2 Output

The outputs of the Step 4 are delivered as follows:

1. *Integrated V-RES Atlas*: three (3) vector files (.shp format), one for each optimization method described above, where solar and wind allocation have been optimized in each Elementary Unit based on the optimization logics described above. The files will report the *KPI-LCOE* [$/MWh] (attribute “LCOE”), the associated potential *KPI-Maximum Installable Capacity* [MW] (attribute “P [MW]”), and the expected *KPI-Yearly energy production* [MWh/year] (attribute “E [MWh]”) of the optimal resource in each Elementary Unit.

7.3 Results and Discussion

The Results for each optimization logic are shown in maps and resuming tables that reports the global values of the three KPIs on the whole territory for solar, wind, and "total" after the optimization performed for each Elementary Unit:

- *Max capacity installable [GW]*: it is the summation of the KPI-Maximum Installable Capacity of each Elementary Units.
- *Max yearly energy producible [TWh]*: it is the summation of the KPI-Yearly energy production of each Elementary Units.
- *Average LCOE [$/kWh]*: it is the weighted average of the KPI-LCOE of each Elementary Unit, weighted based on the KPI-Yearly energy production of each Elementary Unit.

It is important to note that the maps reported below shall be intended as "optionality" V-RES graphs: for each Elementary Unit, each map is meant to provide the V-RES option that maximize the related KPI (being it the KPI-Maximum Installable Capacity, KPI-Yearly energy production, KPI-LCOE). They shall not lead to the conclusion that one V-RES shall be privileged with respect to the other in a given Elementary Unit.

7.3.1 Power optimization (i.e., maximization of KPI-Maximum Installable Capacity as main logic)

The results of the power optimization, shown in Figure 31 and numerically reported in Table 10, depend on the land occupation of the different technologies, whose values are described in paragraph 6.2.1.
From the analysis of the results, it emerges what follows:

- PV plants occupy less area per MW with respect to wind plants: 2.4 ha/MW against around 20 ha/MW (see Table 3 and Table 5). For this reason, in the common areas where both wind and PV plants could be deployed, PV is the optimized solution.
- Among the different types of wind turbines, "Big" turbines have a lower land occupation and are hence preferred in most of the cases. "Small" turbines are only selected where the available area is so small that it could host not even one big turbine, due to the filters applied at the beginning of Step 4 (see Section 6.2.2). The optimized hub height results to be the one that allows to have the wind turbines with the highest IEC Class (Class I and II), that are the ones that have a lower land occupation per MW installed (Table 5) and hence preferred in most of the cases (see the Integrated V-RES Atlas as per output to observe this detail in the attributes of each Elementary Unit). This leads to an optimized hub height of 100 m in most of the Elementary Units.
- The much higher (100 times higher) Max capacity installable of PV plants with respect to wind plants, considering this power optimization criteria leads to a Max yearly energy producible with solar plants around 50 times higher the energy producible with wind plants despite their lower CF.
- From an economic standpoint, this power optimization criterion does not lead to an allocation that is optimal also from a cost minimization-perspective. In fact, the average LCOE of the solar-covered areas is around 12% higher respect to the wind-covered areas, which leads to a global average LCOE that is around 44.5 $/MWh.

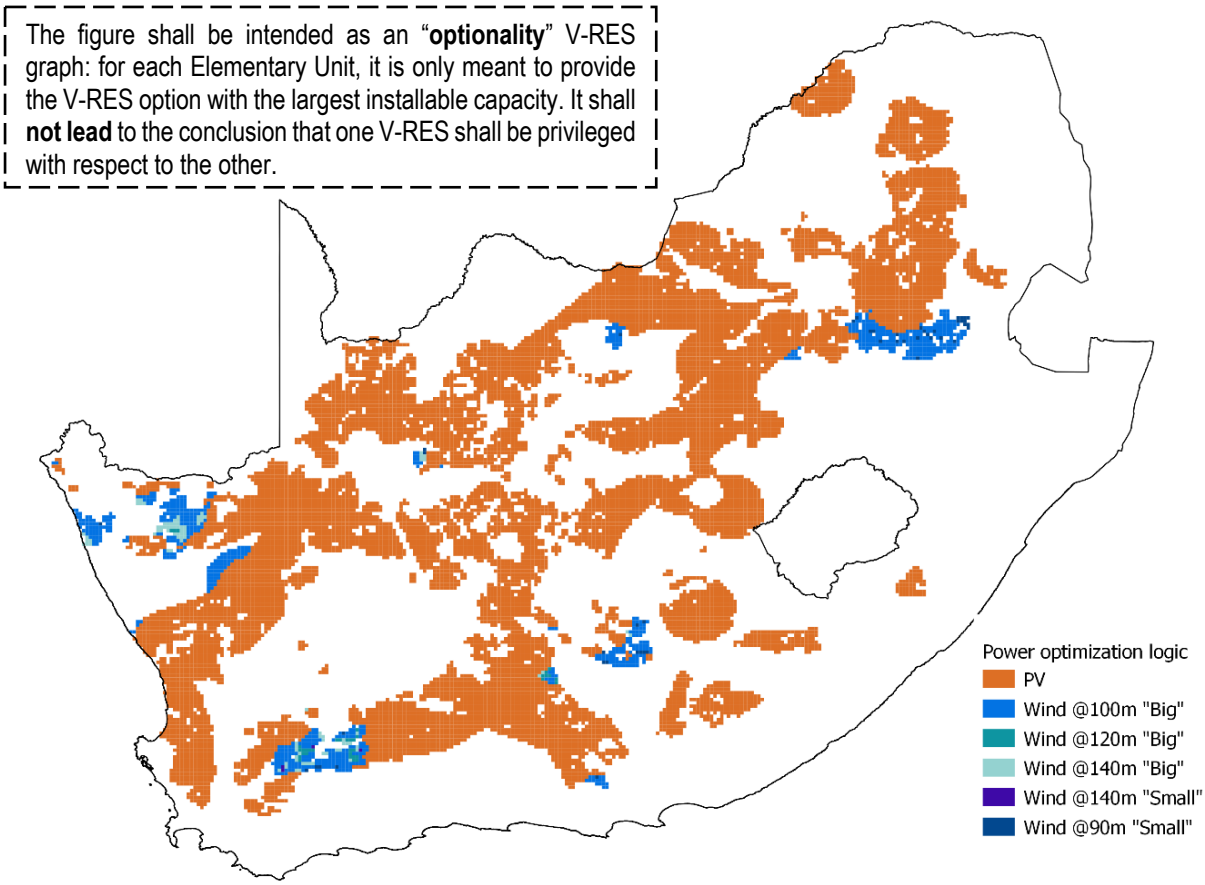


Figure 31 Integrated solar-wind Atlas – "Power optimization" logic.

Table 10 Results – "Power optimization" logic.

OPTIMIZATION LOGIC: *Maximization of KPI-Maximum Installable Capacity*			
Global indicator	**PV**	**Wind**	**TOT**
Max capacity installable [GW]	6418	60	6478
Max yearly energy producible [TWh]	12159	238	12397
Average LCOE [$/MWh]	44.5	39.6	44.4
***NB:** this table reports the resuming results of the "**optionality**" V-RES graph performed with the "Power optimization" logic. It is only meant to provide the values of the resulted KPIs in case the V-RES solution with the largest capacity installable criterion was chosen in each Elementary Unit. The numbers do not represent upper physical limits to the installation of one V-RES with respect to the other.*			

7.3.2 Energy optimization (i.e., maximization of KPI-Yearly energy production as main logic)

The results of the energy optimization are shown in Figure 32 and numerically reported in Table 10. They lead to the following considerations:

- As for the power optimization logic, also with this logic the PV prevails over wind in all the common Elementary Units. This is a direct consequence of the fact that the higher Capacity Factor (CF) of wind in the Elementary Units is not enough to offset the higher KPI-Maximum Installable Capacity of solar in the same Elementary Unit. That is, even with lower capacity

factors, PV plants more efficiently exploit the land producing more energy at a given surface area.

- The previous consideration is reflected in similar numerical results between the two different optimization logics: the maximum capacity installable of both wind and solar plants differs of only 2 GW and the yearly energy production increases of around 37 TWh.
- Among the chosen types of wind turbines there is less variability than in the power optimization logic, since the CF is higher at higher heights, thus moving the optimum towards "Big" and taller turbines. Exceptions are represented by the cases with small available areas where the "Big" turbines cannot be physically installed and therefore the "Small" wind turbines at 140m prevail (only 50 out of 13'900 Elementary Units), and the areas where, due to some presumed inaccuracies in the input data downloaded from WASA, wind resource at 120 m is higher than at 150m and consequently at 140m (only 3 out of 13'900 Elementary Units).
- The selection of taller wind turbines leads to an increase of the LCOE of wind plants with respect to the power optimization logic (from 39.6 $/MWh to 42.5 $/MWh), since, as deeply discussed in Step 4 and Figure 28, LCOE increases with hub height.
- As reported in Section 7.2.1, the optimization performed based on the energy production criterion does not take into account the benefits exploitable from the local integration of different V-RES. As explained in Section 5.2.1 and demonstrated in the case-study included therein, local analysis shall always consider the maximization of grid utilization by looking for configurations where there is complementarity between wind and PV profiles.

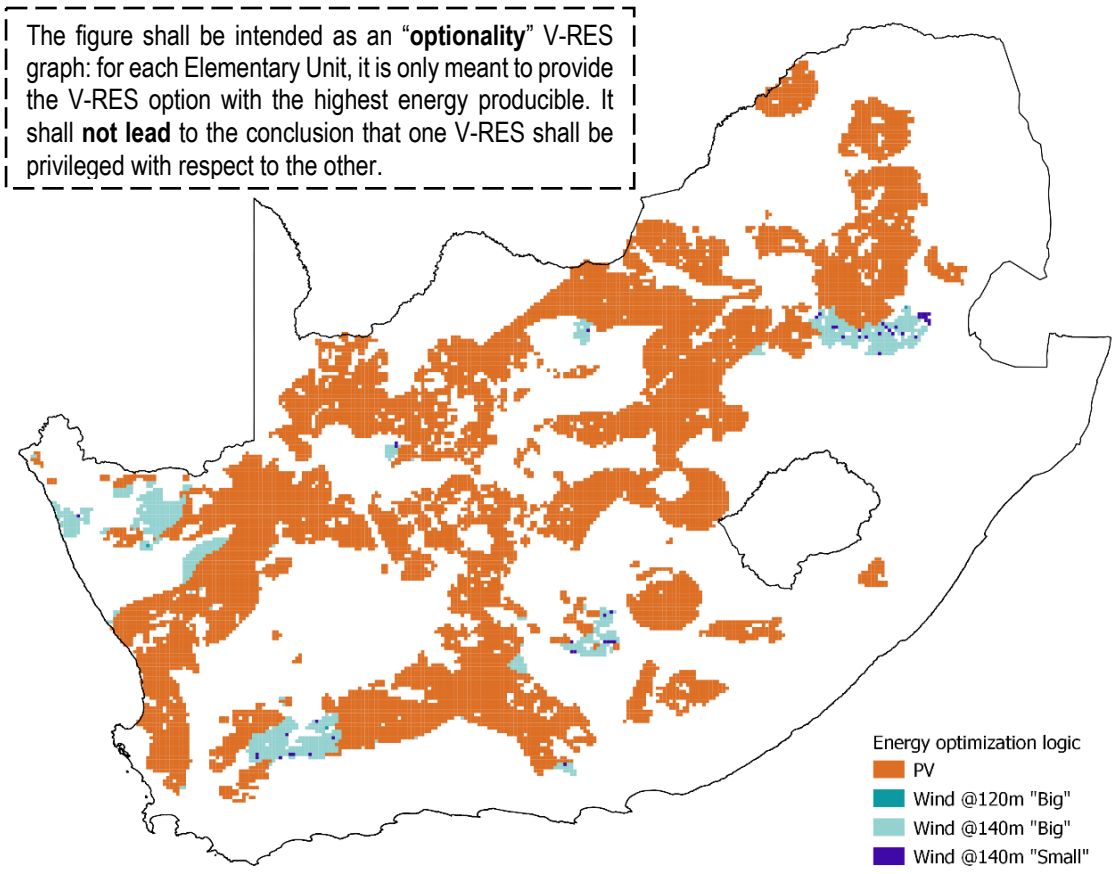


Figure 32 Integrated solar-wind Atlas – "Energy optimization" logic.

Table 11 Results – "Energy optimization" logic.

OPTIMIZATION LOGIC: *Maximization of KPI-Yearly energy production*			
Global indicator	**PV**	**Wind**	**TOT**
Max capacity installable	6415	61	6476
Max yearly energy producible [TWh]	12159	275	12434
Average LCOE [$/MWh]	44.5	42.5	44.5
NB: *this table reports the resuming results of the "**optionality**" V-RES graph performed with the "Energy optimization" logic. It is only meant to provide the values of the resulted KPIs in case the V-RES solution with the highest energy producible criterion was chosen in each Elementary Unit. The numbers do not represent upper physical limits to the installation of one V-RES with respect to the other.*			

7.3.3 Economic optimization (i.e., minimization of KPI-LCOE as main logic)

When looking at the economic optimization logic, where the V-RES that shows the lowest LCOE in each Elementary Unit is selected, the situation deviates radically from the two previous logics (see Figure 33 and Table 12).

From the results it emerges what follows:

- In the Elementary Units where both solar and wind could be exploited, it is wind that has the lowest LCOE in most of the cases: the global max capacity installable of wind increases with respect to the previous cases up to 204 GW.
- Despite this new allocation, solar exploitability remains still much higher than wind in terms of both Max capacity installable and Max yearly energy producible in the country.
- With this optimization logic, the total V-RES Max capacity installable and the Max yearly energy producible are lower respect to the results obtained with the previous two logics. This is a consequence of the fact that the power density of wind installations is lower than solar (i.e., they require more available land per unit of power output), and so a higher number of Elementary Units with wind installations leads to a decrease of global Max capacity installable and Max yearly energy producible.
- The total weighted average LCOE of the country equals 44.1 $/MWh, which does not differ much from the other optimization logics, with 44.4 and 44.5 $/MWh. This is because the LCOE value tends to align to the LCOE of solar resource, due to the consideration of the previous bullet point.
- In terms of variability of LCOE in the country, it ranges from a minimum of 2 7$/MWh in the North Cape and Western Cape provinces to a maximum of 66 $/MWh in the north-eastern part of the country (Figure 34).
- For wind, "Small"-types turbines @ 90 m of hub-height altitude represent the optimized solution almost everywhere, given the lower LCOE at lower hub heights. In few peculiar cases only, the turbine at 100 m and "Big" type is selected where the number of installable "Big" turbines is lower due to space constraints, but with a higher energy yield.

Being the costs, land occupation and energy yield parameters tested as sensitivity parameters, the figures reported below are subject to sensitivity analysis in Section 8 (Ⓢ).

The figure shall be intended as an "**optionality**" V-RES graph: for each Elementary Unit, it is only meant to provide the V-RES option with the lowest average LCOE. It shall **not lead** to the conclusion that one V-RES shall be privileged with respect to the other.

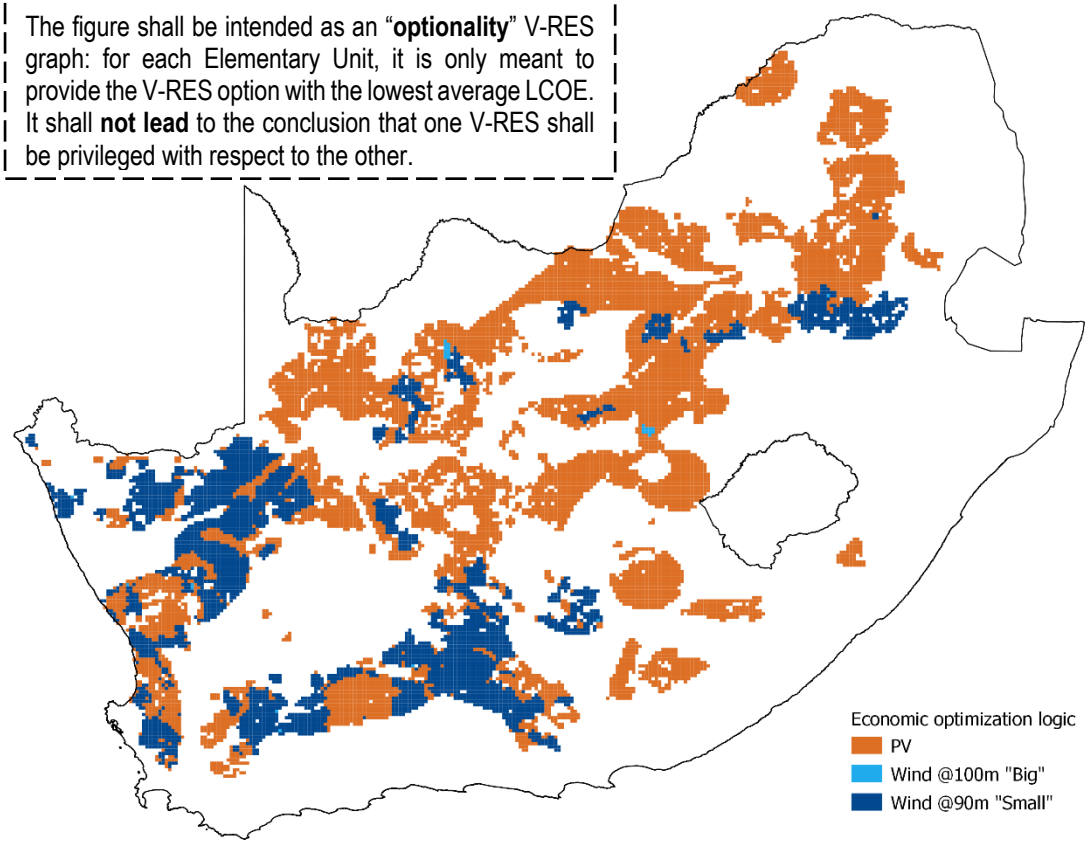


Figure 33 Integrated solar-wind Atlas – "Economic optimization" logic. This map is subject to sensitivity analysis (Ⓢ).

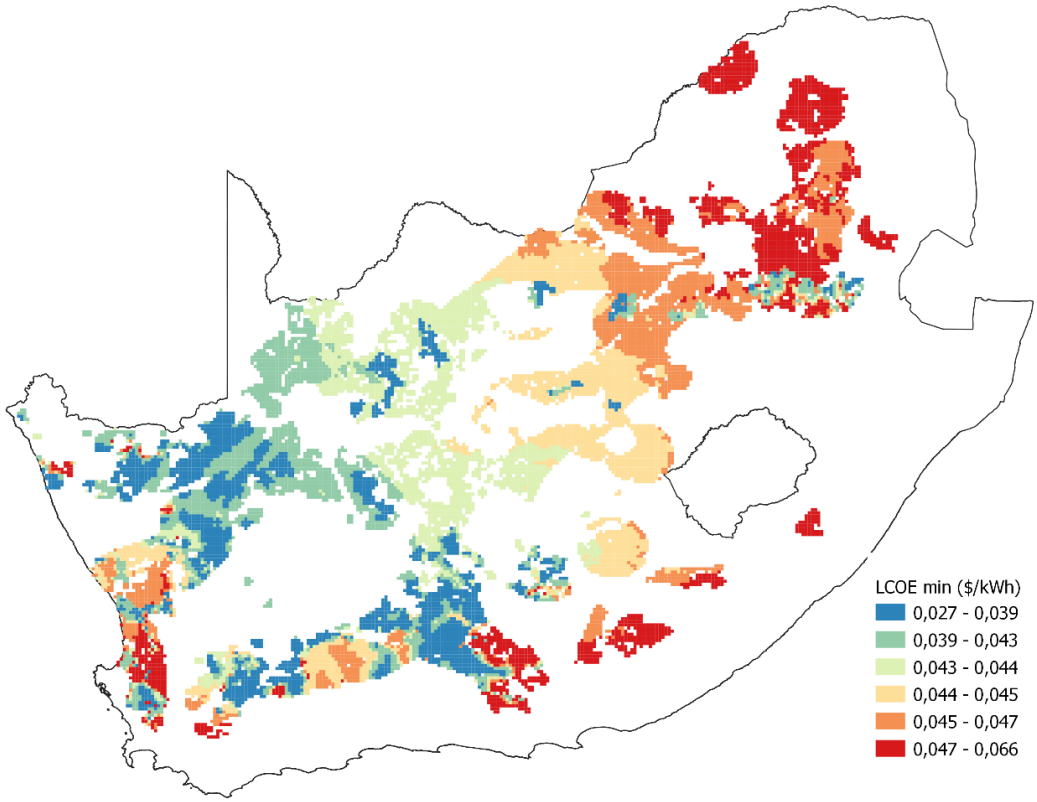


Figure 34 Values of LCOE optimized. This map is subject to sensitivity analysis (Ⓢ).

Table 12 Results – "Economic optimization" logic.

OPTIMIZATION LOGIC: *Minimization of KPI-LCOE*			
Global indicator	**PV**	**Wind**	**TOT**
Max capacity installable [GW]	4485	204	4689
Max yearly energy producible [TWh]	8452	783	9235
Average LCOE [$/MWh]	44.8	36.9	44.1
NB: *this table reports the resuming results of the "**optionality**" V-RES graph performed with the "Economic optimization" logic. It is only meant to provide the values of the resulted KPIs in case the V-RES solution with the lowest LCOE criterion was chosen in each Elementary Unit. The numbers do not represent upper physical limits to the installation of one V-RES with respect to the other.*			

It is stressed again that this analysis performed is a pure numerical optimization, which provides only a binary result (i.e., wind vs PV for each cell) according to a cost minimization criterion. For this reason, the figures above shall not necessarily lead to a conclusion that one source shall be privileged to the other in a given Elementary Unit. To confirm this, next Figure 35 reports the ratio between the LCOE solar and LCOE wind in the areas where both wind and solar can be installed, colouring in grey the areas where the two LCOEs vary of less than ± 15%. As displayed, most of the territory falls within this grey band, meaning that the affordability of one source with respect the other is very similar. Also, the remaining-coloured areas are predominantly blueish, meaning that wind can reach lower LCOE values respect to solar in those areas. In general, from the standpoint of a wind or a solar developer, the figure confirms that the allocation of one V-RES with respect to the other, as reported in the map of Figure 33 and Table 12, shall not represent an upper limit to the opportunities for investing in both affordable wind and solar installations therein.

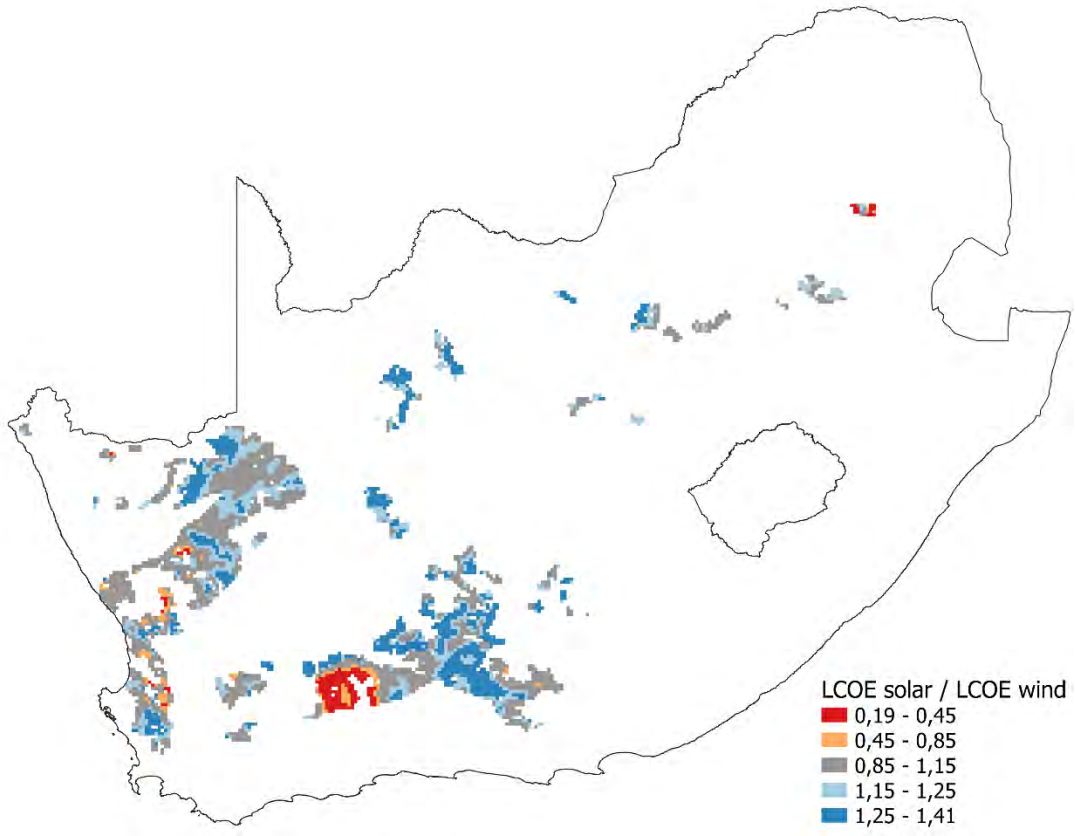


Figure 35 Ratio of LCOE solar / LCOE Wind from the allocation of Figure 33, where both wind and solar can be installed.

7.3.4 Overall Snapshot

This Section just resumes the previous quantitative results in a single snapshot, in order to facilitate the comparison of the different outputs. To correctly interpret the results, it is necessary to recall the initial hypothesis of total Admissible areas for wind and PV, i.e., the total capacity shown in the first graph and the low share of wind with respect to solar, derives not only from the higher land occupation of wind turbines but also from the lower availability of suitable areas for wind turbines installation. Also, it is stressed again that, as reported in Section 7.2.1, the optimizations performed based on the installable capacity and energy production criteria do not take into account the benefits exploitable from the local integration of different V-RES (see Section 5.2.1) and/or the peculiar grid needs that may privilege one source respect to another in different periods of the day. As explained in Section 5.2.1 and demonstrated in the case-study included therein, local analysis shall always consider the maximization of grid utilization by looking for configurations where there is complementarity between wind and PV profiles.

The numbers shall be interpreted at the light of the concept of "**optionality**": for each optimization logic (i.e., Power, Energy, and Economic), the figures are meant to provide the values of the resulted KPIs in case the V-RES solution that optimizes the selected criterion was chosen in each Elementary Unit. The numbers do not represent upper physical limits to the installation of one V-RES with respect to the other. They are interesting for high level planning analysis and scenarios that go beyond the TDP in 2031, as they are much higher than the actual and forecasted generation needs of the country.

Being the land occupation, costs and energy yield parameters tested as sensitivity parameters, the figures reported below are subject to sensitivity analysis in Section 8 (Ⓢ).

This figure reports the resuming results concerning the *KPI-Maximum Installable Capacity* based on the "optionality" V-RES graphs performed with the 3 optimization logics. It is meant to provide the cumulated values of the *KPI-Maximum Installable Capacity* obtained by selecting in every single Elementary Unit the optimal V-RES according to each optimization criterion. The numbers **do not** represent upper physical limits to the installation of one V-RES with respect to the other.

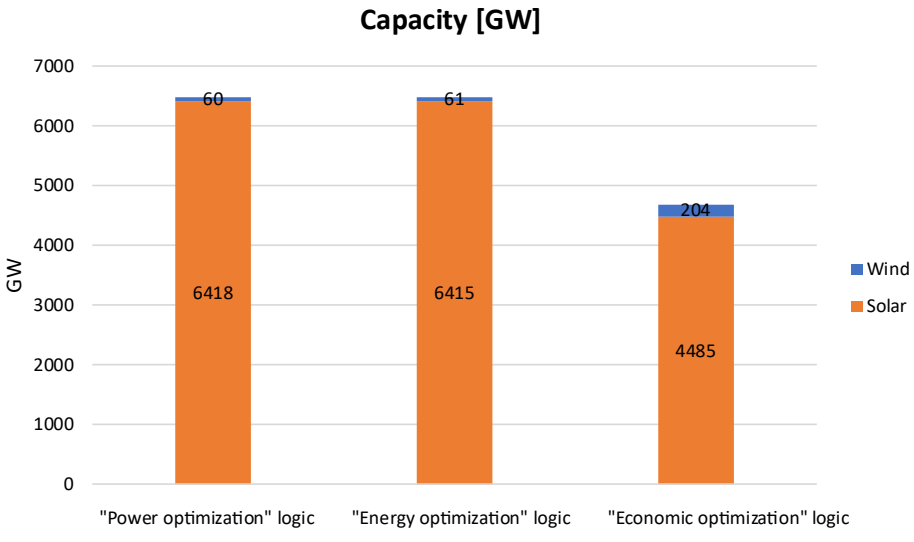


Figure 36. Resume of optimization through Maximization of KPI-Maximum Installable Capacity. This graph is subject to sensitivity analysis (Ⓢ).

This figure reports the resuming results concerning the *KPI-Yearly energy production* based on the "optionality" V-RES graphs performed with the 3 optimization logics. It is meant to provide the cumulated values of the *KPI-Yearly energy production* obtained by selecting in every single Elementary Unit the optimal V-RES according to each optimization criterion. The numbers **do not** represent upper physical limits to the installation of one V-RES with respect to the other.

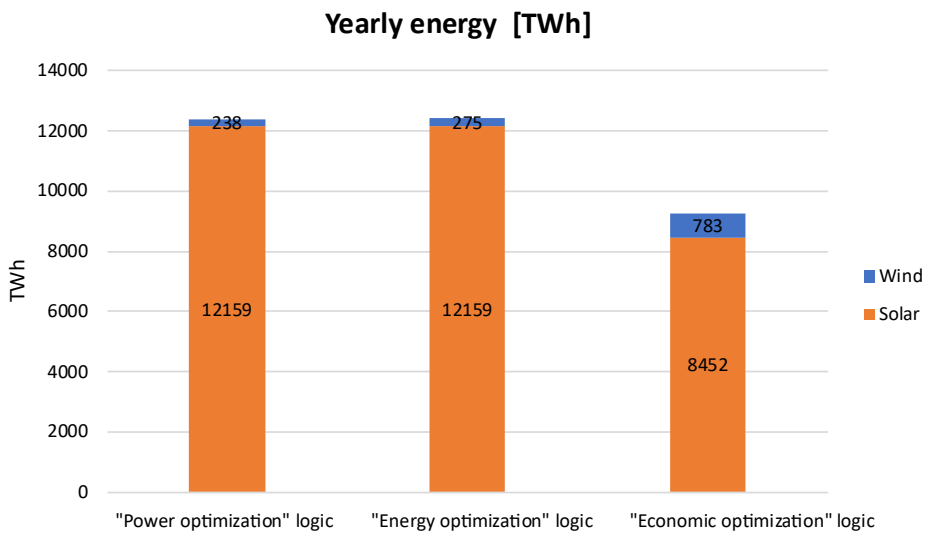


Figure 37 Resume of optimization through Maximization of KPI-Yearly energy production. This map is subject to sensitivity analysis (Ⓢ).

This figure reports the resuming results concerning the *KPI-LCOE* based on the "optionality" V-RES graphs performed with the 3 optimization logics. It is meant to provide the cumulated values of the *KPI-LCOE* obtained by selecting in every single Elementary Unit the optimal V-RES according to each optimization criterion. The numbers **do not** represent upper physical limits to the installation of one V-RES with respect to the other.

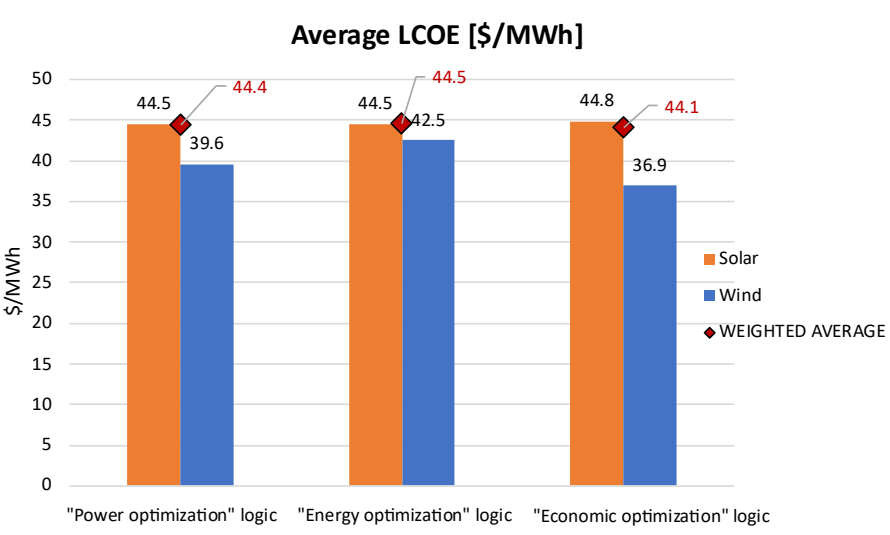


Figure 38 Resume of optimization through Minimization of KPI-LCOE. This map is subject to sensitivity analysis (Ⓢ).

STEP 6: V-RES LOCALISATION AND POWER SYSTEM IMPLICATIONS

7.4 Goal

The Step 6 aims at deriving insights on the most promising locations for the installation of new V-RES plants and assessing the implication of their massive integration on the South African power system from an economic and a grid development perspective. It is important to recall that any quantitative consideration on the impact of the results on the operation of the South African Transmission Grid are excluded from the analysis, since it would require appropriate adequacy and network studies to assess the security of supply and operation of the system with a massive implementation of the V-RES onto the identified locations of the grid. These analyse are out of the scope of this study, as agreed upon with RES4Africa first, and also shared with Eskom.

Within this scope, this Step is approached through the following two analyses with the following specific goals:

1. **Part 1:** Evaluating the most promising locations for the installation of new wind and PV power plants, according to an economic merit-order allocation, refined with considerations on grid proximity. The amount of total capacity installed is constrained according to different Scenarios based on the Integrated Resource Plan (IRP) 2019 [11], from the Department of Mineral Resources and Energy (DMRE), and the Transmission Development Plan (TDP) 2022-2031 from Eskom [12]. The analysis allows to provide insights to support the next grid development plans of the South African power system. Also, the results provide an indication of additional energy fluxes disaggregated at Province level and the average LCOE of new installations, whose values are used in the following sub-step. The latest *TDP2022* (covering the 2023-2032 period), published concurrently to the finalization of this study, substantially increases the target quantities of V-RES in 2031 in South Africa but it is not expected to report conclusions that may impact on the hypotheses and outcomes of this study.
2. **Part 2:** Evaluating the impact of the LCOE on the energy component of the current MEGAFlex tariff. The analysis is performed considering the active energy charge component of the MEGAFlex tariff as currently set by Eskom, expressed in c$/kWh. The analysis is meant to provide a qualitative assessment of the possible expected impact of a certain amount of V-RES deployment in the country, based on the outcomes of the previous point 1 of this Step 6 and the previous Steps of this activity. The tariff impact analysis will also hinge upon the evaluation of the cost of electricity supply for Eskom, considering both the electricity generation quota under Eskom's direct control and Eskom's purchases from Independent Power Producers (IPPs). The electricity supply cost for Eskom is evaluated considering the most updated data and information available on the current generation mix and its supply costs for Eskom, but also considering the possible impact of the market evolutions for fuels/technologies and the environmental costs (national carbon tax component). A key background assumption for this analysis is that the definition of the energy component of the MEGAFlex tariff is linked to the electricity supply costs for Eskom.

7.5 Procedure

7.5.1 Input data processing

The data used as input for the Part 1 of this last Step of the study are the results of the previous steps and the following information:

- *Generation plan from IRP and TDP*: the IRP of 2019 reports the generation targets for conventional and renewable generation in South Africa up to 2031. Those are recalled and readjusted in the latest TDP to consider the decommissioning of plants and the updated REIPPPP installations. The subdivision by province of the generation fleet forecasted in 2031 and reported in the TDP public presentation of 26 October 2021 (Figure 39) is used as first input to set the renewables (PV and wind) targets for the analysis.

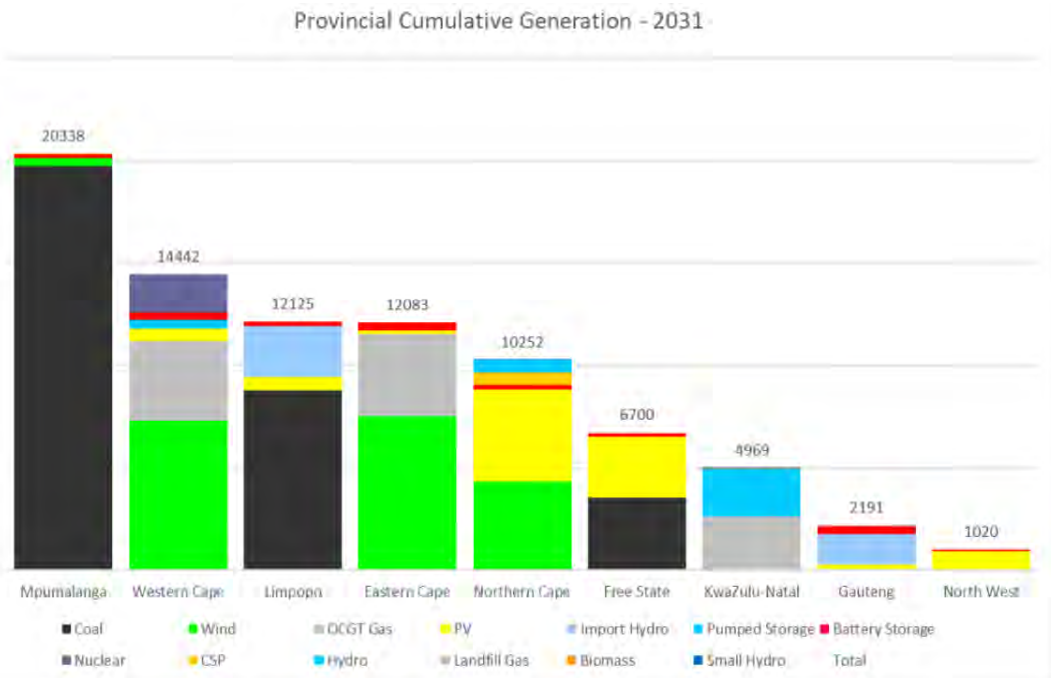


Figure 39 Cumulative new expected capacity [MW] per province up to 2031.

- *IPP plants*: the wind and PV capacity allocated up to the REIPPPP BidW5 (2021) have been considered as already in-place and subtracted from the capacity to be installed up to 2031 of IRP and TDP targets, leading to the following total capacities: tot wind: 14715 MW, and tot PV capacity: 6464 MW). In this way, the residual capacity differs slightly from what reported in TDP, which analyses REIPPPP up to BidW4B (2014).
  The total already installed (or contracted) RES capacity by means of IPP contracts, disaggregated by technology and Province, is shown in Figure 40.

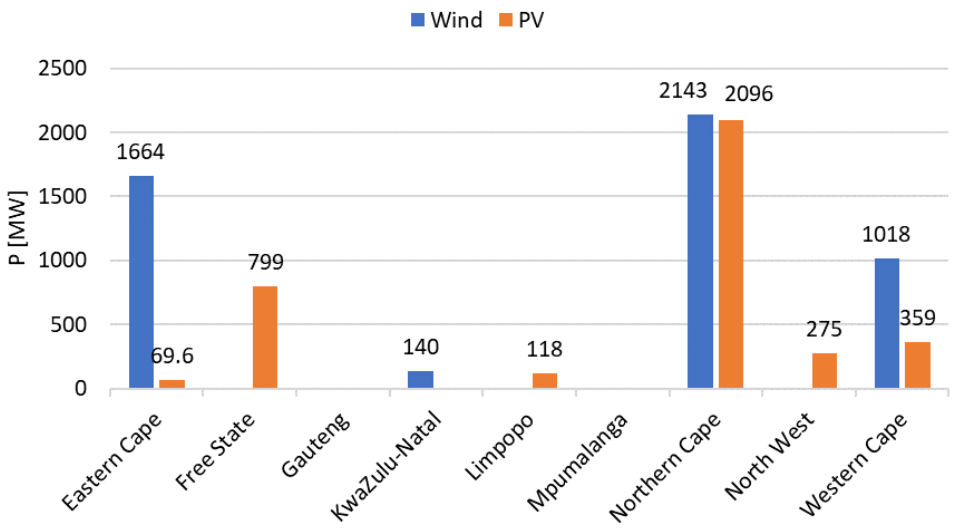


Figure 40 REIPPPP allocated capacity.

- The geospatial data related of the existing and planned transmission network of South Africa, as provided by Eskom, including lines and substations (Figure 41).

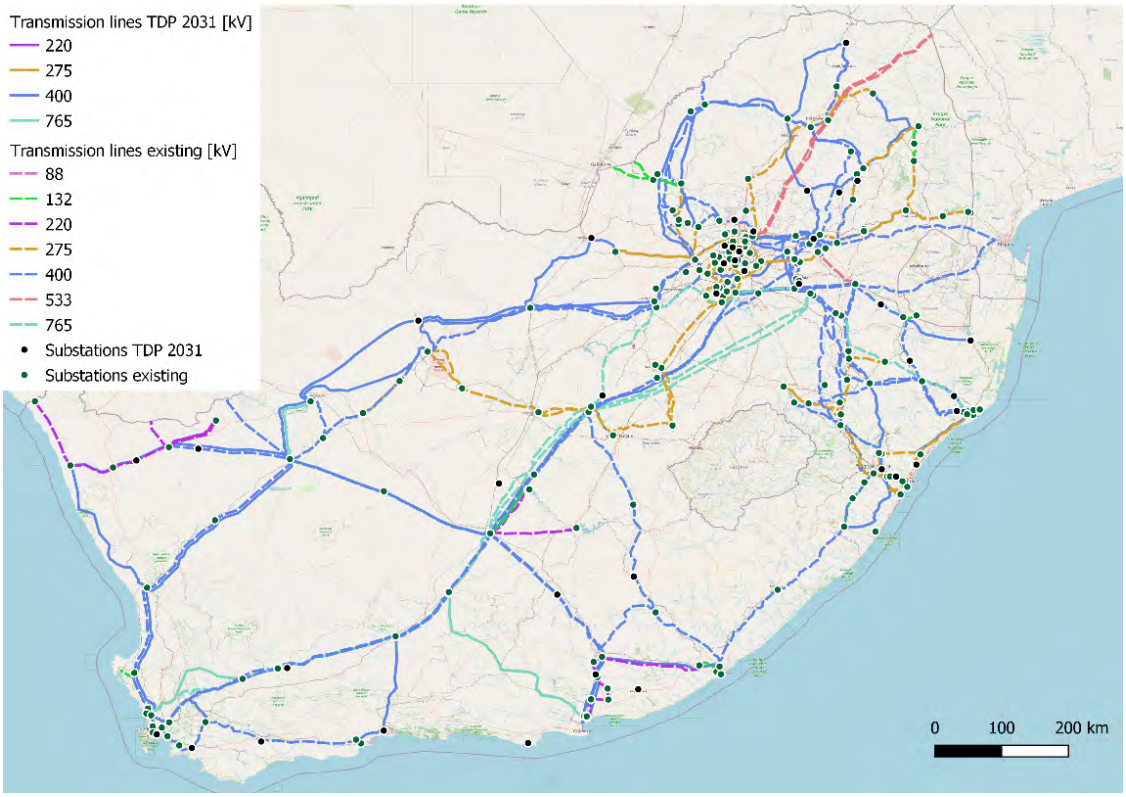


Figure 41 Power system geospatial data.

The data used as input for the Part 2 of this last Step of the study are the following.

- *The values and trend of the energy component MEGAFlex tariff.* The MEGAFlex tariff is for urban customers with contracted maximum demand (or notified maximum demand) greater than 1 MVA. The energy component of the tariff (i.e., the active energy charge) is time-of-use differentiated, based on the voltage of supply and the transmission zone, and is expressed in ZARc/kWh. Table 13 shows the maximum and the minimum values (which vary according to the voltage of supply and the transmission zone) of the MEGAFlex tariff for the two categories of urban users it is devoted to (i.e., local authorities and non-local authorities) in the current period of validity – 1 Apr 2022 - 31 Mar 2023 – and for period 1 Apr 2018 - 31 Mar 2019 [13] [14]. The comparison shows that in the last few years the tariffs totally increased by almost 60% (with an annual increase of around 10%). For the sake of comparison with the rest of the data reported in this report and with the final results, Table 14 shows the same numbers in $/MWh, calculated based on the average exchange rate for the period 2018 – September 2022 (0.0672 USD/ZAR). Figure 42 finally show the peak, standard, off-peak hours in the low and high demand season for the tariff.

Table 13 MEGAFlex Tariff maximim and minimum values for 2022-2023 and 2018-2019 (ZARc/kWh).

Megaflex – Local Authority		**Active energy charge - ZARc/kWh (vat excluded values)**					
Period of validity of the tariff	**max / min**	**High demand season** [Jun - Aug]			**Low demand season** [Sep - May]		
		Peak	**Standard**	**Off Peak**	**Peak**	**Standard**	**Off Peak**
1 Apr 2022 - 31 Mar 2023	max	488.22	147.92	80.32	159.28	109.61	69.55
1 Apr 2022 - 31 Mar 2023	min	426.46	129.19	70.15	139.11	95.74	60.73
1 Apr 2018 - 31 Mar 2019	max	308.72	93.53	50.79	100.71	69.31	43.98
1 Apr 2018 - 31 Mar 2019	min	269.66	81.69	44.36	87.96	60.54	38.41
% variation		58%	58%	58%	58%	58%	58%
Megaflex – Non-Local Authority		**Active energy charge - ZARc/kWh (vat excluded values)**					
Period of validity of the tariff	**max / min**	**High demand season** [Jun - Aug]			**Low demand season** [Sep - May]		
		Peak	**Standard**	**Off Peak**	**Peak**	**Standard**	**Off Peak**
1 Apr 2022 - 31 Mar 2023	max	470.48	142.58	77.38	153.49	105.62	67.03
1 Apr 2022 - 31 Mar 2023	min	410.94	124.47	67.61	134.09	92.26	58.54
1 Apr 2018 - 31 Mar 2019	max	301.22	91.28	49.55	98.27	67.62	42.92
1 Apr 2018 - 31 Mar 2019	min	263.11	79.7	43.29	85.85	59.07	37.48
% variation		56%	56%	56%	56%	56%	56%

Table 14 MEGAFlex Tariff maximim and minimum values for 2022-2023 and 2018-2019 (US$/MWh).

Megaflex – Local Authority		**Active energy charge - US$/MWh (vat excluded values)**					
Period of validity of the tariff	**max / min**	**High demand season [Jun - Aug]**			**Low demand season [Sep - May]**		
		Peak	**Standard**	**Off Peak**	**Peak**	**Standard**	**Off Peak**
1 Apr 2022 - 31 Mar 2023	max	328.08	99.40	53.98	107.04	73.66	46.74
1 Apr 2022 - 31 Mar 2023	min	286.58	86.82	47.14	93.48	64.34	40.81
1 Apr 2018 - 31 Mar 2019	max	207.46	62.85	34.13	67.68	46.58	29.55
1 Apr 2018 - 31 Mar 2019	min	181.21	54.90	29.81	59.11	40.68	25.81
% variation		58%	58%	58%	58%	58%	58%
Megaflex – Non-Local Authority		**Active energy charge - US$/MWh (vat excluded values)**					

Period of validity of the tariff	max / min	High demand season [Jun - Aug]			Low demand season [Sep - May]		
		Peak	Standard	Off Peak	Peak	Standard	Off Peak
1 Apr 2022 - 31 Mar 2023	max	316.16	95.81	52.00	103.15	70.98	45.04
1 Apr 2022 - 31 Mar 2023	min	276.15	83.64	45.43	90.11	62.00	39.34
1 Apr 2018 - 31 Mar 2019	max	202.42	61.34	33.30	66.04	45.44	28.84
1 Apr 2018 - 31 Mar 2019	min	176.81	53.56	29.09	57.69	39.70	25.19
% variation		56%	56%	56%	56%	56%	56%

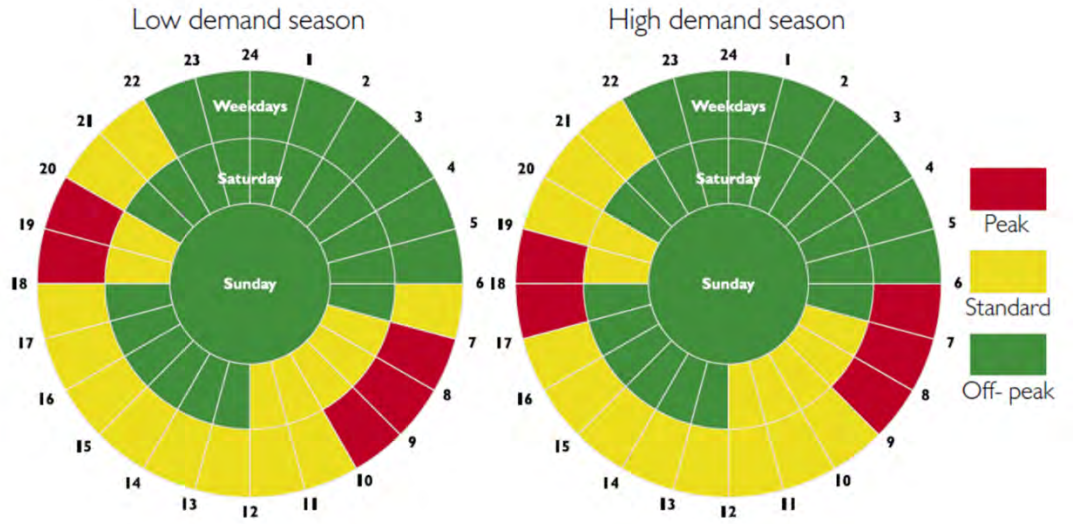


Figure 42 Peak, Standard, Off-peak hours in low and high demand seasons for MEGAFlexTariff.

Data on the electricity generation mix in South Africa. Eskom's website reports the hourly generation per source/technology starting from 1 April 2018, allowing to see the current electricity generation mix in the country and its recent trend. Figure 43 provides an overall overview of the monthly trend of electricity generation in South Africa per source / technology from April 2018 to September 2022. The generation mix in the country is largely dominated by coal, but in the recent years there has been an increase in the V-RES generation with the REIPPPP (see Figure 44, where only the solar and wind and generation is portrayed).

- Table 15 reports the annual total electricity balance for South Africa, including electricity imports and exports form / to neighbouring countries, splitting the OCGT generation into the ESKOM part and the IPP part, and the solar generation into the PV and CSP technologies. Finally, Table 16 shows the total installed capacity by renewables technology / source from 2018 till September 2022.

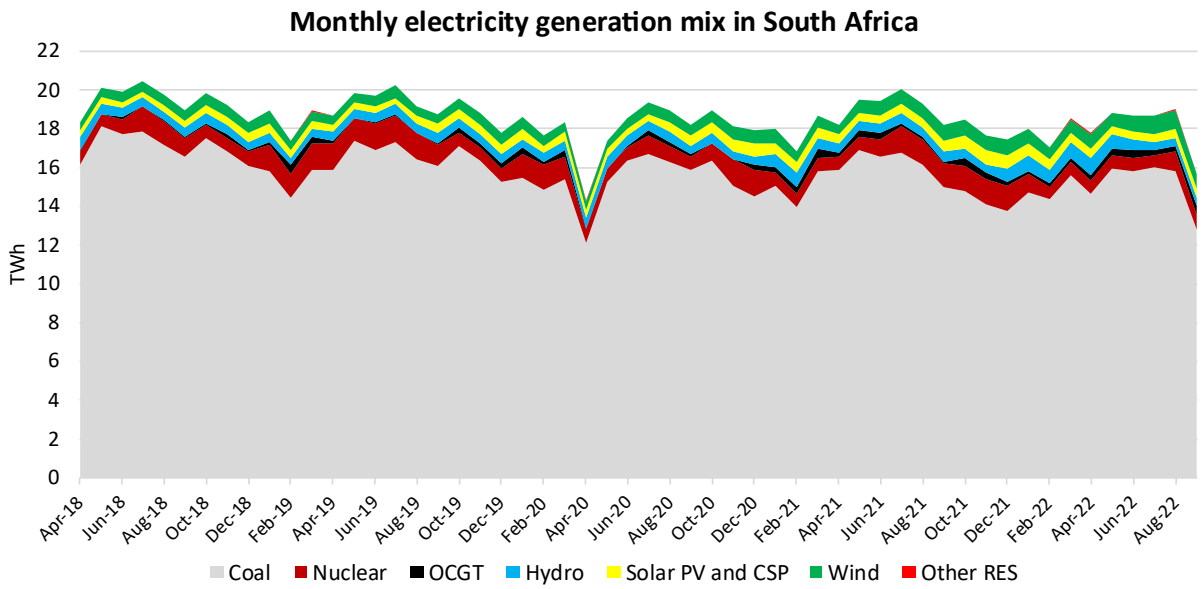


Figure 43 Total monthly electricity generation trend per source/technology in South Africa (April 2018 – September 2022).

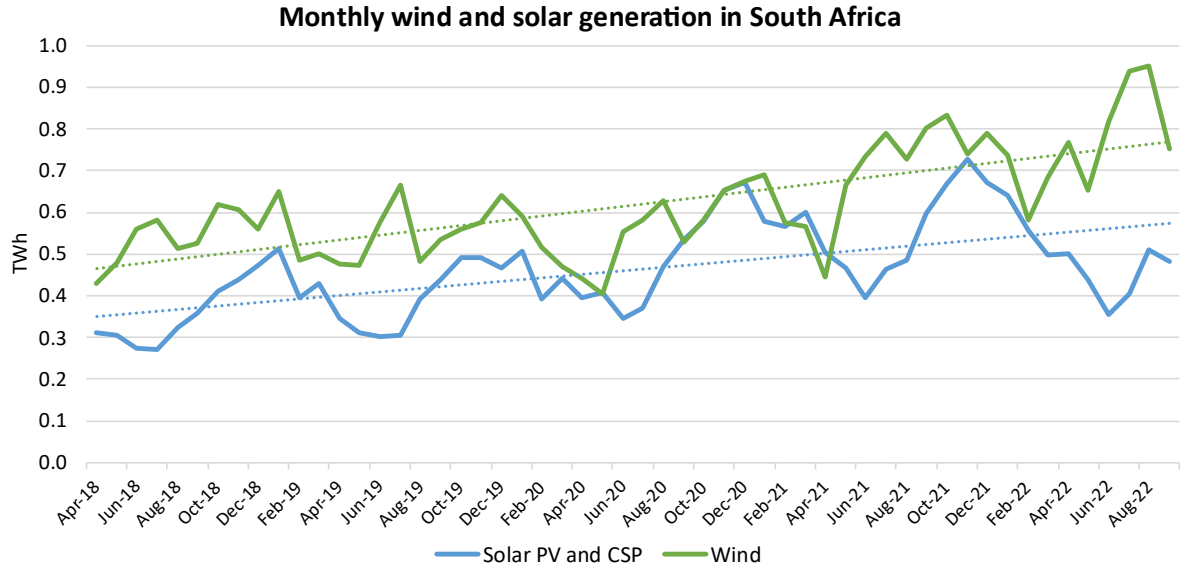


Figure 44 Total monthly electricity generation from solar and wind in South Africa (April 2018 – September 2022)

*Table 15 Annual electricity mix in South Africa [TWh] (*2022: up to September).*

[TWh]	Coal	Nuclear	Eskom OCGT Generation	Dispatchable IPP OCGT	Hydro	Solar PV	Solar CSP	Wind	Other RES	Import	Export
2019	194.91	13.59	1.54	0.61	5.62	3.32	1.56	6.62	0.08	9.83	15.00
2020	184.41	11.51	1.25	0.66	5.89	5.77	1.63	6.63	0.09	9.89	13.65
2021	184.68	12.16	2.24	0.98	6.48	6.73	1.66	8.36	0.12	10.15	13.71
2022*	135.73	6.61	1.95	0.73	5.67	4.39	0.97	6.89	0.15	8.12	9.17

*Table 16 Total renewable generation capacity installed in South Africa [MW] (*2022: up to September).*

[MW]	Wind	Solar PV	Solar CSP	Other RES	TOTAL
2018	2080	1474	400	22	**3976**
2019	2080	1474	500	22	**4076**
2020	2495	2032	500	22	**5049**
2021	3023	2212	500	26	**5761**
2022*	3443	2212	500	51	**6205**

- *Current variable electricity supply cost for Eskom.* Eskom Integrated Reports [15] [16] [17] [18] provide data on the "primary energy unit cost of the various generation categories" for Eskom, including the generation directly owned and managed by Eskom, as well the electricity Eskom purchases from IPPs (OCGT and renewables), and from abroad. For Eskom generation, the costs are mainly related to the primary energy costs (fuels costs), while the unit costs of IPPs and international purchases are based on the full cost of operation[5]. The costs are referred to the financial year from 1 April to 31 March (therefore 2021/2020 is considered from 1 April 2020 to 31 March 2021). Table 17 and Table 18 show the electricity supply costs for Eskom per source in the last few years in local currency and in in $/MWh. It is well noteworthy how the variable costs for coal and nuclear generation and for the electricity imports are just a fraction of the costs for OCGTs (both Eskom's and IPP's ones), and renewables from IPPs. The costs of electricity supply from IPPs depend on the results of the REIPPPP (preferred bidders tariffs) and the other IPP programs.

Table 17 Variable electricity supply costs per source for Eskom in the last few fiscal years (ZAR/MWh).

[Unit cost, ZAR/MWh]	2021/2020	2020/2019	2019/2018	2018/2017
Coal	421	397	339	309
Nuclear	105	100	103	94
Eskom-owned OCGTs	2778	3231	3128	2313
IPPs	2280	2347	2200	2015
IPP OCGTs	*3579*	*4049*	*4344*	*2926*
Renewable IPPs	*2178*	*2206*	*2058*	*2005*
International purchases	567	550	509	358

Table 18 Variable electricity supply costs per source for Eskom in the last few fiscal years ($/MWh).

[Unit cost, $/MWh]	2021/2020	2020/2019	2019/2018	2018/2017
Coal	28.3	26.7	22.8	20.8
Nuclear	7.1	6.7	6.9	6.3
Eskom-owned OCGTs	186.7	217.1	210.2	155.4
IPPs	153.2	157.7	147.8	135.4
IPP OCGTs	*240.5*	*272.1*	*291.9*	*196.6*
Renewable IPPs	*146.4*	*148.2*	*138.3*	*134.7*
International purchases	38.1	37.0	34.2	24.1

[5] As highlighted by Eskom in the Integrated Report, IPP and international purchases are treated as a variable cost in Eskom's accounts, therefore this treatment to compare variable costs of generation is considered appropriate.

- *REIPPPP BidW5*. The results (List of Preferred Bidders) of the latest REIPPPP Bid Window (BidW5 were announced on 28 October 2021, and as at today Bid Window 6 is open for potential bidders to register. As discussed above, in Section 6.3, BidW5 resulted in a much lower *fully indexed tariff* (ZAR/MWh) compared to BidW4 and the previous Bid Windows. The impact of such results, which entail a decrease in the supply costs of renewables generation from IPPs for Eskom, are not included in the data shows in the previous point (on the Eskom's variable electricity supply cost), since they were published after the latest available Integrated Report, and also because they are not yet operational according to the IPP Project Database[6]. Table 19 and Table 20 summarize the key results of REIPPPP BidW5, with the tariff data reported first in ZAR/MWh and then in $/MWh based on the 2021 exchange rate (0.0677 USD/ZAR).

Table 19 Overall results of REIPPPP BidW5 – tariffs in ZAR/MWh.

Technology	Fully Indexed Tariff [ZAR/MWh]			Total contracted capacity [MW]
	Average	Max	Min	
Onshore Wind	494	618	344	1608
Solar PV	431	485	375	975

Table 20 Overall results of REIPPPP BidW5 – tariffs in $/MWh.

Technology	Fully Indexed Tariff [$/MWh]			Total contracted capacity [MW]
	Average	Max	Min	
Onshore Wind	33	42	23	1608
Solar PV	29	33	25	975

- *Total electricity demand in South Africa and expected renewables generation in 2031.* According to data provided by Eskom the total electricity demand in South Africa in 2031 should be equal to around 259 TWh (which corresponds to an expected growth of 1.3% per year as compound annual growth rate from the latest available historical data for 2021 of RSA Contracted Demand, equal to 227 TWh).

7.5.2 Methodology (Part 1)

The selection of the most promising locations for V-RES plants, as well as to the estimation of their LCOE and possible impact on the power system, has been performed according to 4 stages:

Stage 1: Spatial distribution through economic Merit-order

The first stage considers the identification of 2 Scenarios of V-RES localization in the Admissible areas:

- **Scenario 1**: this is the Scenario that better reflects the IRP and TDP targets. The amount of total generation capacity of PV and Wind plants to be reached in 2031 in each Province follows the quantities reported in Figure 39. The residual capacity to be installed in each Province is given by the difference between those targets (Figure 39) and the current capacity already allocated (Figure 40). The results are shown in Figure 45. The geospatial distribution of the total capacity per Province within the area of each Province is performed through the merit-order criteria

[6] https://www.ipp-projects.co.za/ProjectDatabase.

applied to *Integrated V-RES Atlas* obtained with the Economic optimization logic in Step 5 (see Section 7) (i.e., the Atlas obtained by allocating wind and solar based on the least *KPI-LCOE* [$/MWh] in each Elementary Unit).

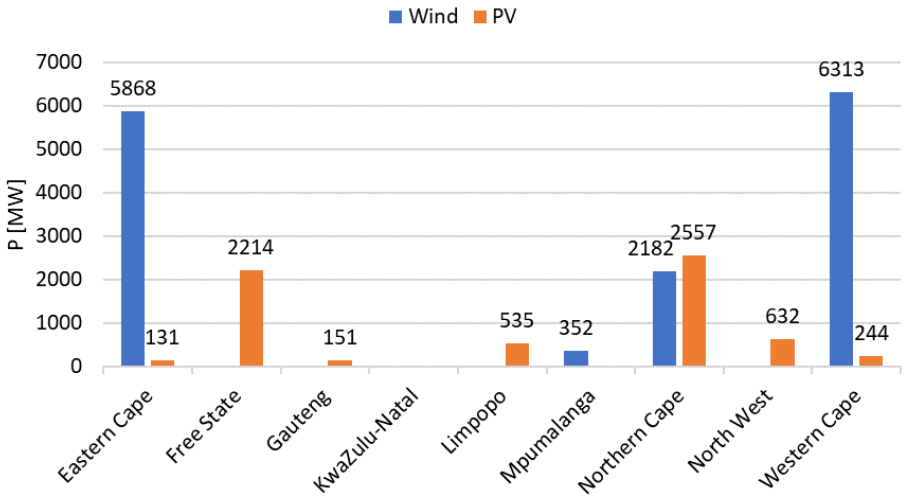


Figure 45 Scenario 1: PV and Wind capacity to be installed.

- **Scenario 2**: this Scenario is similar to the previous one but skipping over the allocation by Province indicated in the IRP/TDP. The scenario considers therefore the aggregated residual total capacity to be installed up to 2031 for Wind and PV plants in South Africa according to IRP/TDP, net of latest REIPPPP BidW5, while it leaves free the distribution of the capacity in the Admissible areas to follow an economic merit order in the whole country – i.e., allocation in each Elementary Unit through the merit-order criteria applied directly to *Integrated V-RES Atlas* obtained with the Economic optimization logic in Step 5 (see Section 7).

Stage 2: Re-allocation based on Grid proximity

The results of the previous state are critically analysed evaluating the proximity of the selected areas to the existing and planned transmission grid. Two proximity areas are considered:

1. *Distance to the grid lower than 50 km*: within this distance, it is assumed that the additional cost for connecting new power plants to the grid is not critically affecting the total installation cost. The localization of V-RES in the Elementary Units of this 0-50km corridor performed in the previous stage based on the pure economic merit-order is hence maintained.
2. *Distance to the grid higher than 50km*: this distance may start to become relevant in terms of cost implications for the grid extension. The capacity of wind and PV plants that in the previous stage was allocated in the Elementary Units outside the 0-50km corridor is redistributed into the lowest-cost Elementary Units inside the corridor. The incremental LCOE is then computed.

Stage 3: Considerations on grid impact

The results of each scenario in terms of geospatial distribution of the V-RES targets in the country are finally discussed from the perspective of existing and planned grid, in order to provide a first indication of the transmission grid corridors that may be mostly affected from the new clusters of V-RES installations.

It shall be noticed that both the allocations performed in Stage 1 and 2 are meant to provide preliminary insights to Eskom on the possible most suitable areas for V-RES installation. As indicated in Section 7.4, detailed adequacy and network studies to assess at quantitative level the impact of these results on the security of supply and operation of the system are out of the scope of this study, as agreed upon with RES4Africa first, and shared with Eskom.

Stage 4: Evaluation of RES installations cost-opportunity

The last stage consists of evaluating the differential cost of installing V-RES plants in the North-Eastern part of the country (grey area in Figure 46), which is the area in South Africa where the majority of the load and transmission grid infrastructure is concentrated but where the availability and exploitability of V-RES is scarcer, with respect to the optimal solutions identified in the previous stage. That area is in fact the one that is less promising from natural resources standpoint since the Admissible area for PV and wind installations is less than in the Western part of South Africa (pink area in Figure 46), and both solar irradiation and wind speed are weaker. However, installing V-RES in the North-East area is expected to require less investments for infrastructure reinforcement, at the expense of a higher LCOE of the energy produced.

The goal of this analysis is therefore to support Eskom in identifying the optimal trade-off between installing V-RES plants in areas (West side) with high availability of V-RES but far from the load centres, with respect to installing plants in areas with higher LCOE (North-East side) but closer to the load centres and therefore requiring less investments on grid reinforcement. In other words, such differential cost can be intended as a proxy of the cost-opportunity for investing in grid infrastructure to reinforce the West-East corridor.

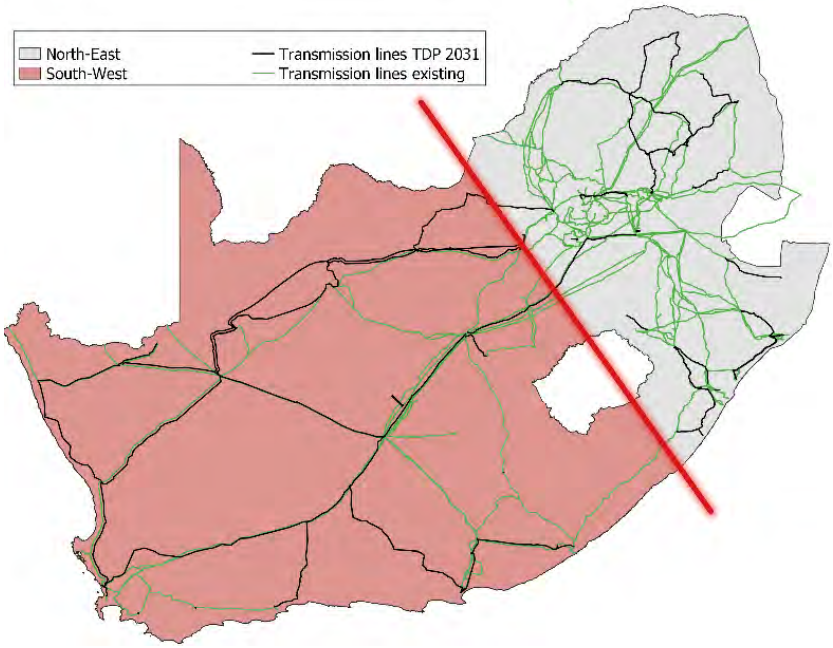


Figure 46 South Africa North-East and South-West areas. The line has been elaborated based on Eskom indications.

The analysis consists of reallocating all the Elementary Units for PV and wind installations identified in Scenario 1 (the one respecting the IRP and TDP targets by Province) in the North-Eastern area. Given the expected lower energy produced by V-RES in the North-East for the same capacity installed, V-RES targets are set in terms of total energy produced (that is set to be equal to the one of Scenario 1). To be conservative, the analysis investigates the extreme case: even in case the Admissible areas for V-RES in

the North-East are not enough for covering the required energy production, all the capacity is still supposed to be reallocated with the average LCOE and CF of the North-Eastern area.
The LCOE obtained with these hypotheses is then compared to the LCOE of Scenario 1 to evaluate the cost difference and consequently the breakeven cost for infrastructure reinforcements in the West-East corridor that would make the two solutions equivalents, net of the possible minor reinforcements that are anyhow necessary for accommodating massive V-RES plants in the North-East area.

7.5.3 Methodology (Part 2)

Analysing and combining all the available data as described in the previous Section allows to assess the increase in the electricity supply costs in the last few years and its roots. This analysis of the supply cost compositions and trend is possible only for the period from April 2018 to March 2021, that is the period for which the variable electricity supply cost as per the Eskom Integrated Reports are currently available.

Figure 47 portrays and recaps the latest average variable energy supply costs in South Africa, allowing a snapshot overview of the relevant differences between technologies and sources. From this overview it can be clearly stated that in the analysed period, the renewable IPPs (but also OCGTs) had the effect to increase the average generation costs. Nevertheless, it is important to point out that these figures report the variable generation unitary costs. Based on discussion with RES4Africa, it emerged that in the latest years the conventional power plants (mainly coal) are subjected to a frequent program of extraordinary maintenance that reduced considerably the actual availability of these plants. This effect is not captured in the variable cost indicator, but it has a direct impact on the increase of the cost of electricity supply.

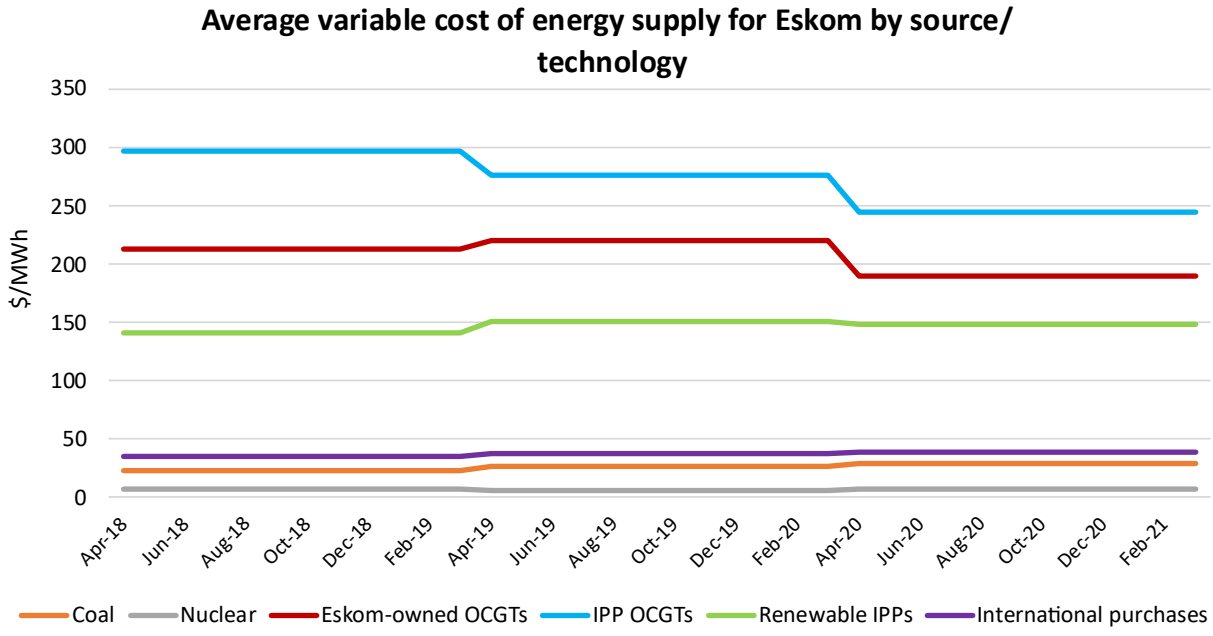


Figure 47 Average variable cost of energy supply for Eskom by source/ technology (based on Eskom data from Integrated Report 2018, 2019, 2020, 2021).

Figure 48 depicts the generation trend (on a total monthly basis) of coal, wind, solar and all renewables over the same period, showing an overall decreasing trend for coal and an increasing trend for all renewables. The total generation per source depends on the total electricity demand of the country and on the net import/export balance, and usually the traditional thermal generation (coal for South Africa)

is the resulting difference between the total demand and the renewables generation. Therefore, other things being equal (demand, import/export), an increase in renewables generation (due the deployment of new renewable capacity and/or to favourable weather conditions) brings about a decrease in the traditional thermal generation. Considering the current cost of electricity supply in South Africa, such trends concurred to increase in the weighted average electricity generation supply cost. This consideration emerges also from Figure 49, which shows the weighted average variable supply cost on monthly basis, which can easily be linked to the increasing share of renewables in the power generation mix of South Africa, and only partially to increase in the coal generation cost of the last few years. As per Figure 47, also these figures report the variable generation unitary costs, without including the "unavailability" factor of conventional coal power plant.

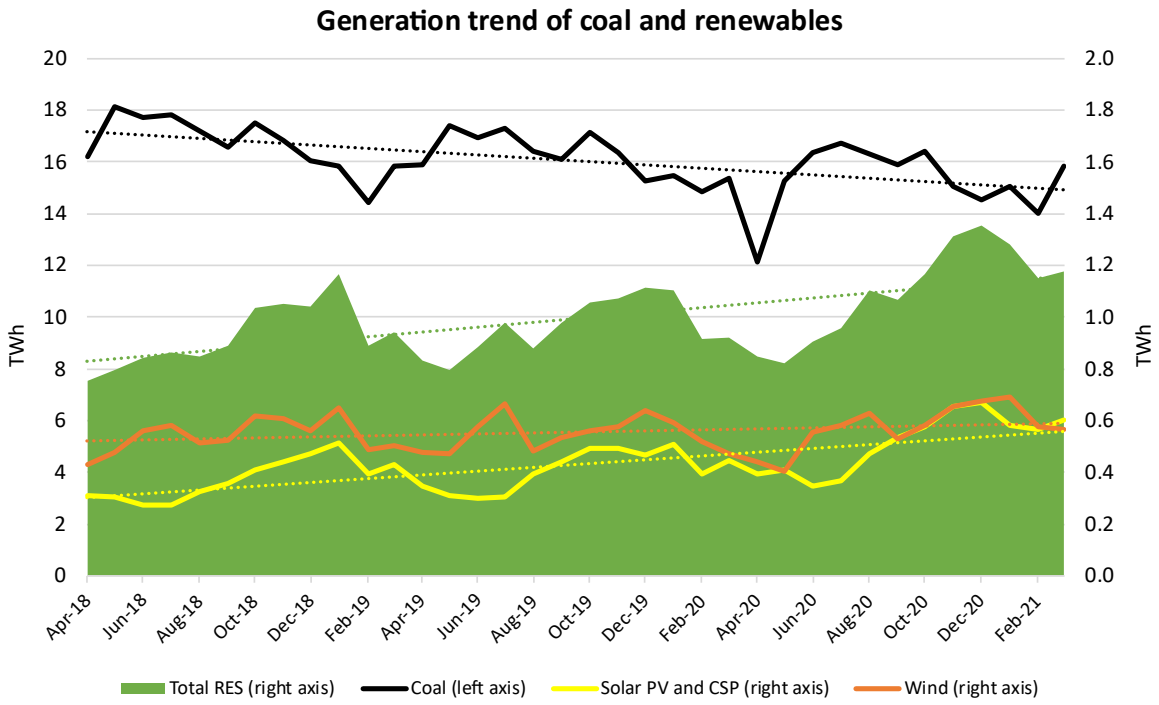


Figure 48 Generation trend of coal and renewables.

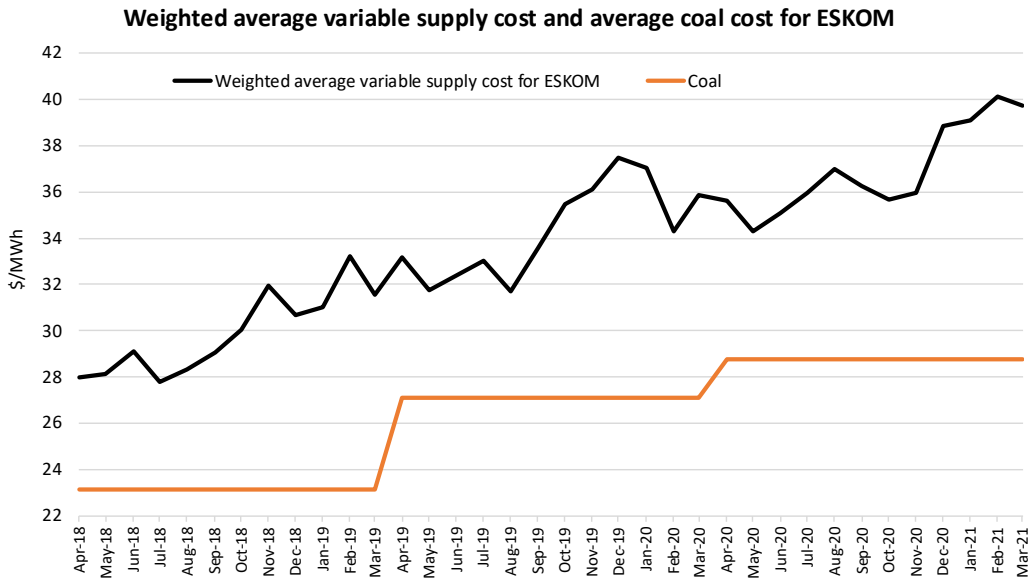


Figure 49 Weighted average variable supply cost and average coal cost for Eskom (based on Eskom data from Integrated Report 2018, 2019, 2020, 2021).

Overall, it is possible to report the following conclusions from the available data on costs and generation of the last few years in South Africa:

- The weighted average cost of electricity supply for Eskom has been increasing from April 2018 to March 2021.
- In the same period the electricity generation from V-RES has been increasing, thanks to the commissioning of new solar and wind and other RES power plants.
- The procurement of new V-RES plants contributed to increase the total weighted average costs of electricity.
- Also, the increase of cost of coal contributed to increase the weighted average cost of electricity supply.
- The increase in the energy component MEGAFlex tariff of the last few years is at least partially linked to the increased costs of energy procurement from V-RES IPPs.

Once analysed the factor influencing the energy supply cost in South Africa, the following analysis is performed to assess the impact of the new 20 GW of V-RES that are expected to connect to the South Africa power system by 2031:

- Calculation of the decrease of the total weighted VREs-average supply costs based on the REIPPPP BidW5 results and the expected LCOE of the new VREs plants calculated after the optimal geospatial allocation performed in the Part 1 of this Step 6. The hypothesis is that all the new V-RES capacity will get a contract with Eskom for selling its renewable electricity to it as it is happening today with the REIPPPP, and assuming the calculated LCOE as direct proxy of awarded fully indexed tariff for the projects and, as a consequence, of the energy component of the tariff.
- Impact of the V-RES generation cost on the coal-based generation, considering the expected electricity demand in South African of 2031 and the expected increase in the cost of coal by 2031. The following hypotheses are considered for this analysis:

- The cost of V-RES by 2031 is the one estimated in this study. This is of course a preventive hypothesis since the cost of V-RES by 2031 is expected to lower due to the observed decreasing trend in the V-RES technology costs in the recent years.
- The grid will be able to evacuate the total power generated by the new V-RES.
- The share of new generation from V-RES will cover the expected increase of electricity demand and replace coal in the first instance.
- Regarding the cost of coal, the above reported data from Eskom Integrated Reports show an increase for the variable costs of electricity supply costs of coal as which is equal to a compound annual growth rate (CAGR) of 11% in the three years' time span between the 2018/2017 and 2021/2020 fiscal years. Based on the recent market trends (and geopolitical tensions), and the fact that tight market conditions are expected to endure in the following years[7], CESI assumed this annual trend to continue up 2031, which would lead to an electricity generation cost from coal of 79 $/MWh in 2031.

7.5.4 Output

1. *Selected Areas Atlas*: six (6) vector files (.shp format) with the Elementary Units selected in each scenario (Scenario 1, Scenario2 and Scenario 1-Stage2) for wind a PV resources, with associated the installed power (attribute "P [MW]"), the energy produced (attribute "E [MWh]") and the LCOE (attribute "LCOE")) and the total Admissible Area (attribute "Area m^2]").
2. *Centroid Atlas*: six (6) vector files (.shp format) with the centroids of power of wind and PV installations, with associated the associated capacity.

7.6 Results and Discussions

7.6.1 Results (Part 1)

This Section reports the results concerning the localization of V-RES into the South African power system and considerations on the potential implications on the grid.

Starting from the output of the first Scenario of *Stage 1: Spatial distribution through economic Merit-order*, the allocation of the total net capacity of IRP/TDP targets by Province based on the least-cost merit order criterion lead to results shown in Figure 50 – which localizes only the Elementary Units allocated for V-RES –, Figure 51 – which displays the capacities of the localized plants in the Elementary Units –, and numerically reported in Table 21.

[7] https://www.iea.org/reports/coal-market-update-july-2022/prices

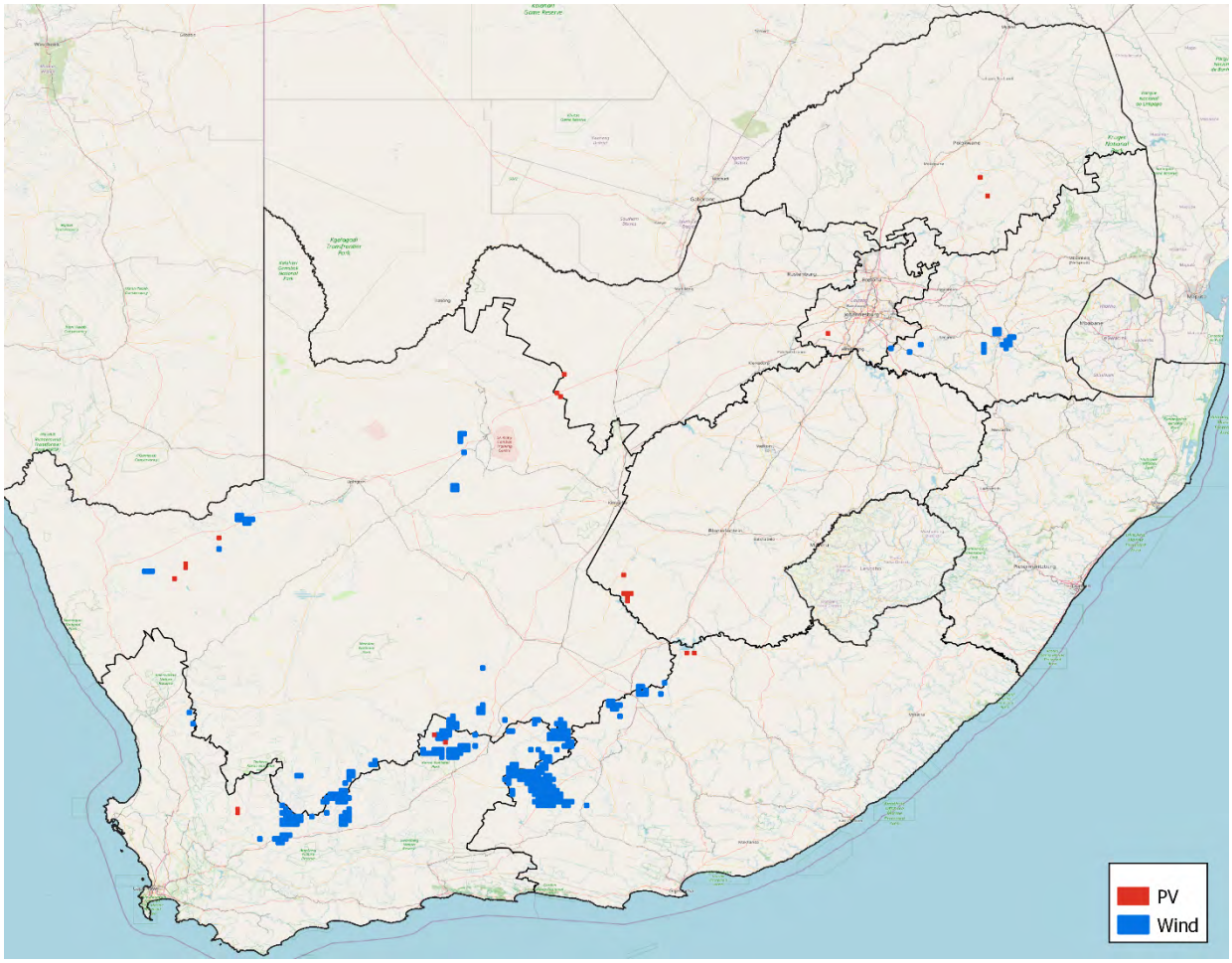


Figure 50 Scenario 1 (with IRP Province constraints), Stage 1 (w/o grid proximity considerations): selected Elementary Units for localizing V-RES.

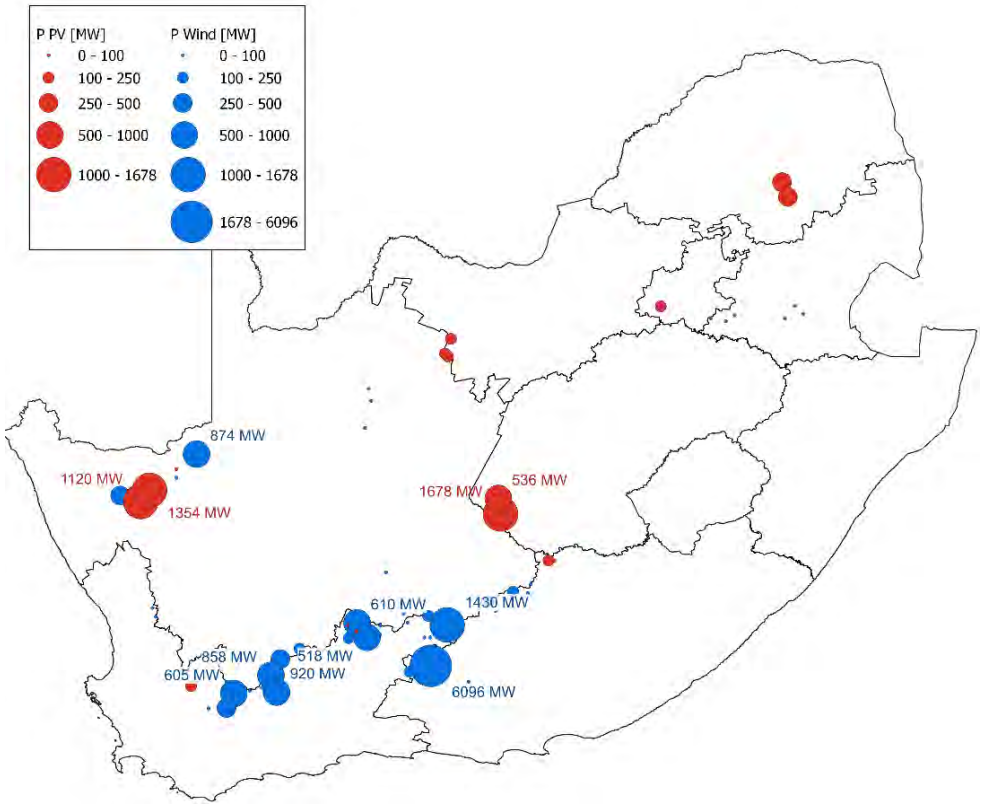


Figure 51 Scenario 1 (with IRP Province constraints), Stage 1 (w/o grid proximity considerations): installed capacities of localized V-REs. This map is subject to sensitivity analysis in Section 8 (Ⓢ).

Table 21 Results of Scenario 1 (with IRP Province constraints), Stage 1 (w/o grid proximity considerations). This table is subject to sensitivity analysis in Section 8 (Ⓢ).

	Solar PV				Wind			
Provinces	**P [MW]**	**LCOE [$/MWh]**	**Energy [GWh]**	**Area [km²]**	**P [MW]**	**LCOE [$/MWh]**	**Energy [GWh]**	**Area [km²]**
Eastern Cape	131	44.0	252	3.1	5868	33.2	24980	1047
Free State	2214	44.0	4244	53.0	0	0.0	0	0
Gauteng	151	46.2	276	3.6	0	0.0	0	0
KwaZulu-Natal	0	0.0	0	0.0	0	0.0	0	0
Limpopo	535	46.3	975	12.8	0	0.0	0	0
Mpumalanga	0	0.0	0	0.0	351.5	36.1	1374	63
Northern Cape	2557	41.7	5173	61.2	2182	29.6	10412	376
North West	632	43.8	1219	15.1	0	0.0	0	0
Western Cape	244	43.3	475	5.8	6313	30.5	29194	1086
TOT	**6464**	**43.2**	**12613**	**154.7**	**14715**	**31.5**	**65961**	**2573**

Cape is the Province that is expected to allocate the largest area for V-RES localization, mainly wind farms, and it turns out to be the Province with the highest V-RES capacity penetration. Eastern Cape follows, with almost 6 GW of wind plants localized in the north of the Province. The expected capacity of solar PV is almost equally split between Free State (around 2.2 GW) and Northern Cape (around 2.5 GW), which in turns is expected to host also 2 GW of wind farm.

As explained in the methodology in Section 7.5.2, the Scenario 1 builds upon the hypothesis of allocation of total V-RES capacity by respecting the IRP target for each Province. Scenario 2 relaxes this constraint, leaving the optimization algorithm to allocate the total net V-RES capacity in all the Admissible areas of the country according to a least-cost merit order based on the LCOE values calculated in Step 5 (Section 7). The results of the selection of the most promising locations and expected capacity installed according to Scenario 2 are shown in Figure 52, Figure 53, and numerically reported in Table 22. Also, Figure 54 (wind) and Figure 55 (solar PV) reports the comparison between the results of the two Scenarios, together with a discussion on the results.

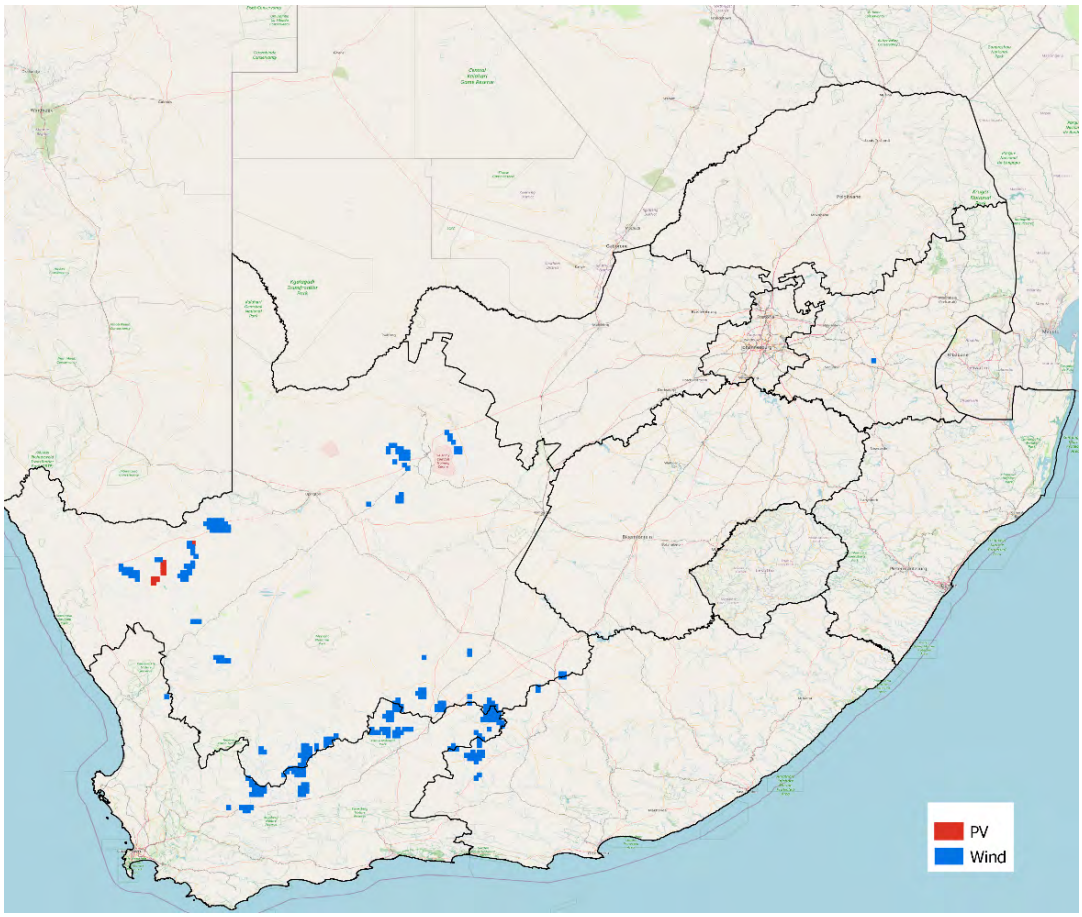


Figure 52 Scenario 2 (w/o IRP Province constraints), Stage 1 (w/o grid proximity considerations): selected Elementary Units for localizing V-RES.

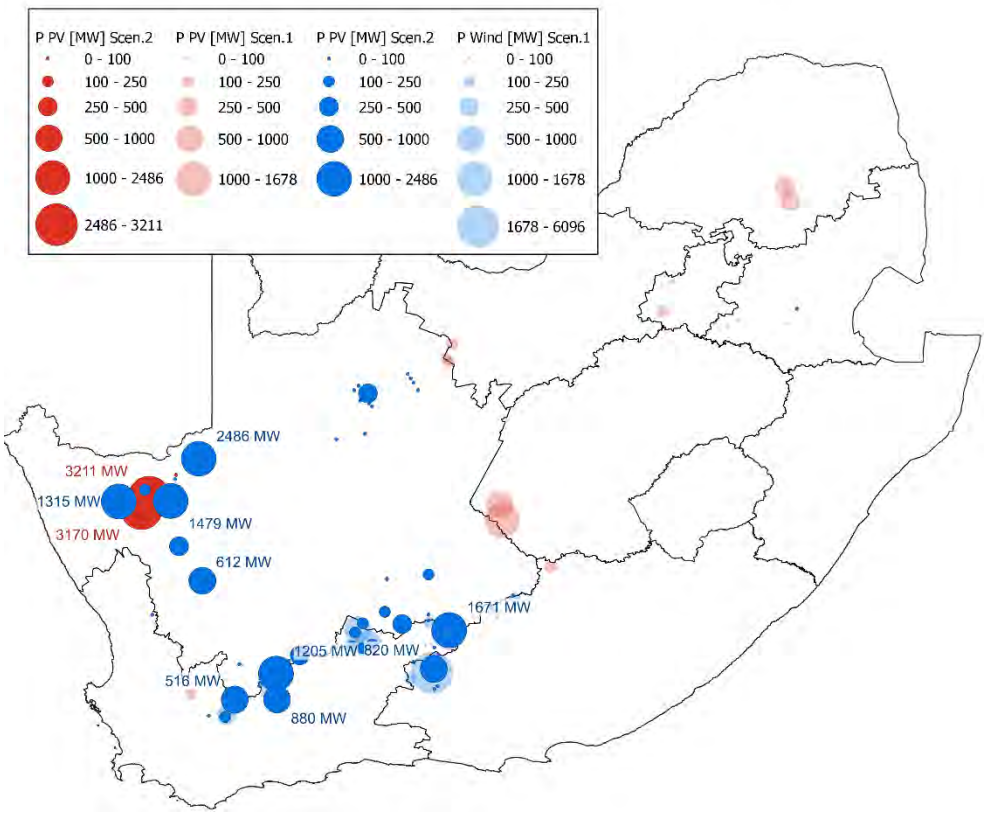


Figure 53 Scenario 2 (w/o IRP Province constraints), Stage 1 (w/o grid proximity considerations): installed capacities of localized V-REs.

Table 22 Results of Scenario 2 (w/o IRP Province constraints), Stage 1 (w/o grid proximity considerations).

	Solar PV				Wind			
Provinces	**P [MW]**	**LCOE [$/MWh]**	**Energy [GWh]**	**Area [km^2]**	**P [MW]**	**LCOE [$/MWh]**	**Energy [GWh]**	**Area [km^2]**
Eastern Cape	0	0.0	0	0.0	1025	30.6	4737	182
Free State	0	0.0	0	0.0	0	0.0	0	0
Gauteng	0	0.0	0	0.0	0	0.0	0	0
KwaZulu-Natal	0	0.0	0	0.0	0	0.0	0	0
Limpopo	0	0.0	0	0.0	0	0.0	0	0
Mpumalanga	0	0.0	0	0.0	0	31.1	0	0.02
Northern Cape	6464	41.7	13071	154.7	9179	30.6	42346	1624
North West	0	0.0	0	0.0	0	0.0	0	
Western Cape	0	0.0	0	0.0	4510	29.9	21284	765
TOT	**6464**	**41.7**	**13071**	**154.7**	**14715**	**30.4**	**68368**	**2572**

According to Scenario 2, Northern Cape is the Province that is expected to allocate the largest area for V-RES localization: all the total capacity of Solar PV (6.5 GW) envisaged in the IRP/TDP, net of the REIPPPP BidW5, is expected to be hosted in Northern Cape, together with around 62% of the total capacity of wind (9.2 GW out of 14.7 GW). Northern Cape is in fact the Province with the highest Solar PV and wind potential (on average), and the Economic optimization performed in Section 7.3.3 potentially allocates

a very large fraction of both solar and wind in the Province. Western Cape follows, with almost 4.5 GW of wind plants localized in the north-central part of the Province.

With respect to Scenario 1, the relaxation of the IRP Province-boundary constraint leads to the obvious conclusion that the least-cost localization of V-RES converges towards the areas with the highest V-RES potential (and lowest LCOE), that are mainly concentrated in Northern Cape. In fact, all (for solar)/most (for wind) of the Elementary Units in Northern Cape allow to have a better *KPI-Yearly energy production* at same *KPI-Maximum Installable Capacity*, thus reducing the *KPI-LCOE* for both solar and wind technologies. Nevertheless, the effective benefits of Scenario 2 with respect to Scenario 1 in terms of Max yearly energy producible [TWh] (around 5% higher for both V-RES) and Average LCOE [$/MWh] (around 4% lower for both technologies) are negligible[8].

In general, we can conclude that given the well-known grid congestion challenges that the South African power system is experiencing, in case a disaggregate V-RES distribution within or among the Provinces could release or avoid worsening some of the congestions, there would be much room to avoid consequences in terms of higher average cost of electricity by handling the installation of the plants in areas with low LCOE. This emerges clearly from Figure 56 for solar PV, where the selected Elementary Units for localizing solar in Scenario 1 are surrounded by large areas with the same/similar LCOE values. Also Wind has some degree of freedom (Figure 57), but not so huge as the one solar PV, since the selected Elementary Units for localizing wind in Scenario 1 in each Province already cover the areas with the lowest LCOE values.

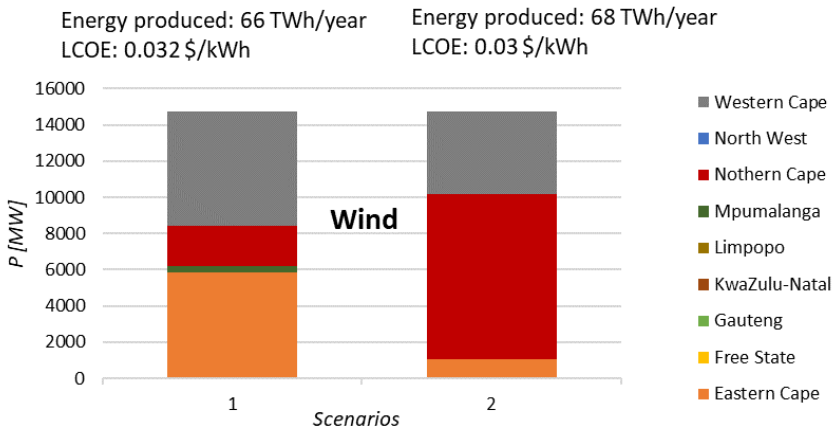


Figure 54 Scenarios 1 & 2 comparison, wind.

[8] Note: the economic considerations based on the LCOE does not consider side effects of a less disperse allocation as per Scenario 2, such as the possibility to benefit from better economies of scales and prioritize economic convenience in fewer locations.

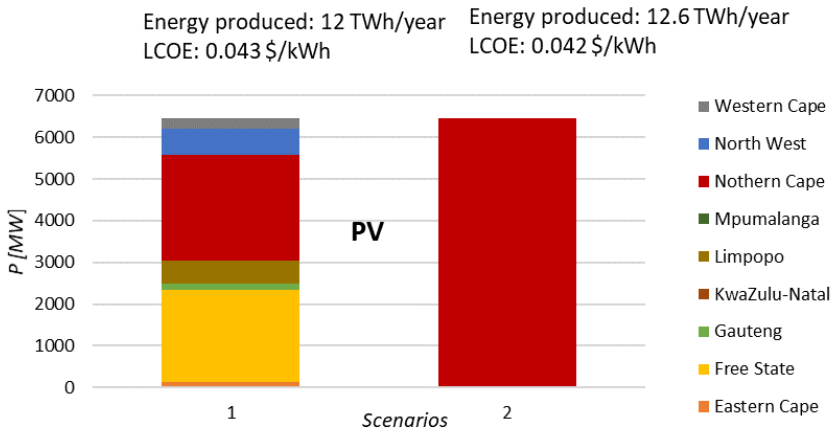


Figure 55 Scenarios 1 & 2 comparison, PV.

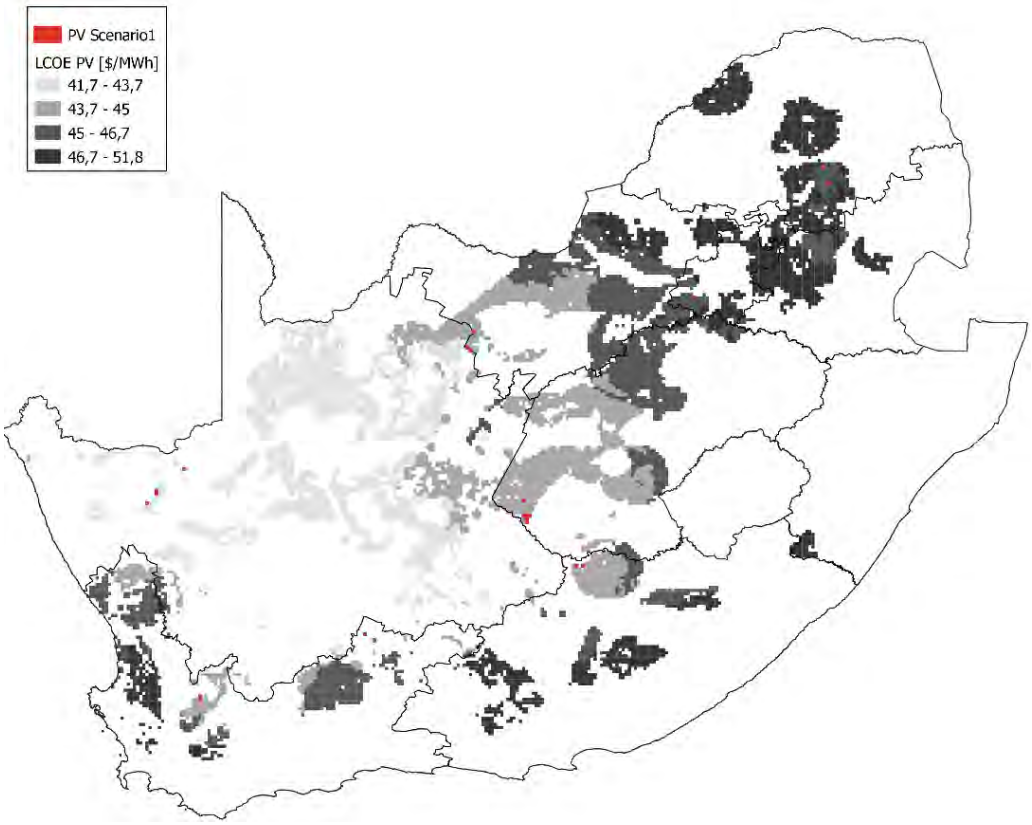


Figure 56 LCOE levels-map, solar.

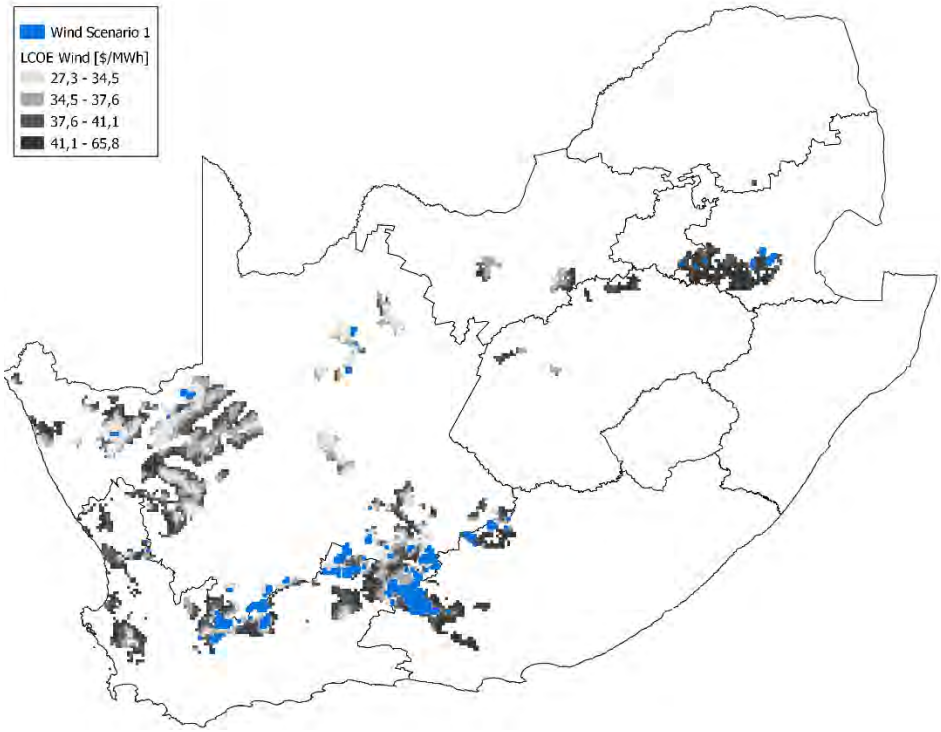


Figure 57 LCOE levels-map, wind.

The previous considerations shall be read net of grid implications. That is the reason why the methodology of this Part 1 included also a *Stage 2: Re-allocation based on Grid proximity*, which aimed at refining the results of Scenario 1 of *Stage 1* by introducing some grid proximity considerations. Figure 58 reports the same Figure 50 with the selected Elementary Units for localizing V-RES of Scenario 1 (with IRP Province constraints), Stage 1 (w/o grid proximity considerations), together with the transmission lines (existing and planned), 50 km grid proximity corridors, and substations (existing and planned). The yellow arrows point the expected V-RES installations that are outside the 50 km-corridors, comprising a total of 1.8 GW of wind and 1.1 GW of solar PV capacity.

The geospatial re-allocation within the 50 km-corridors following the least-cost driven path is reported in Figure 59, with the resulted re-allocated V-RES capacities displayed in Figure 60, and numerically reported in Table 23.

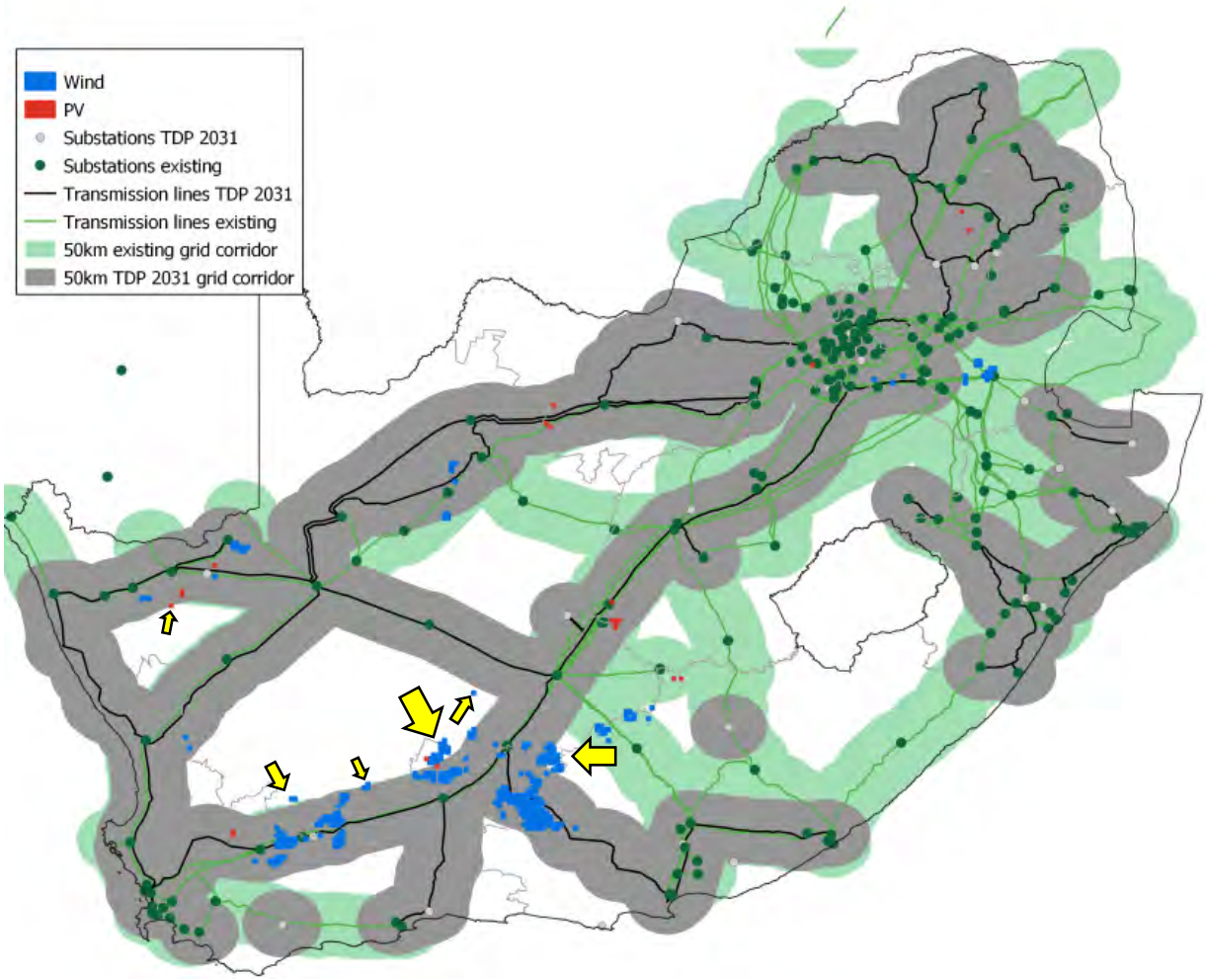


Figure 58 Scenario 1 (with IRP Province constraints), Stage 1 (w/o grid proximity considerations): transmission lines, grid proximity corridors, substations, and Elementary Units for localizing V-RES.

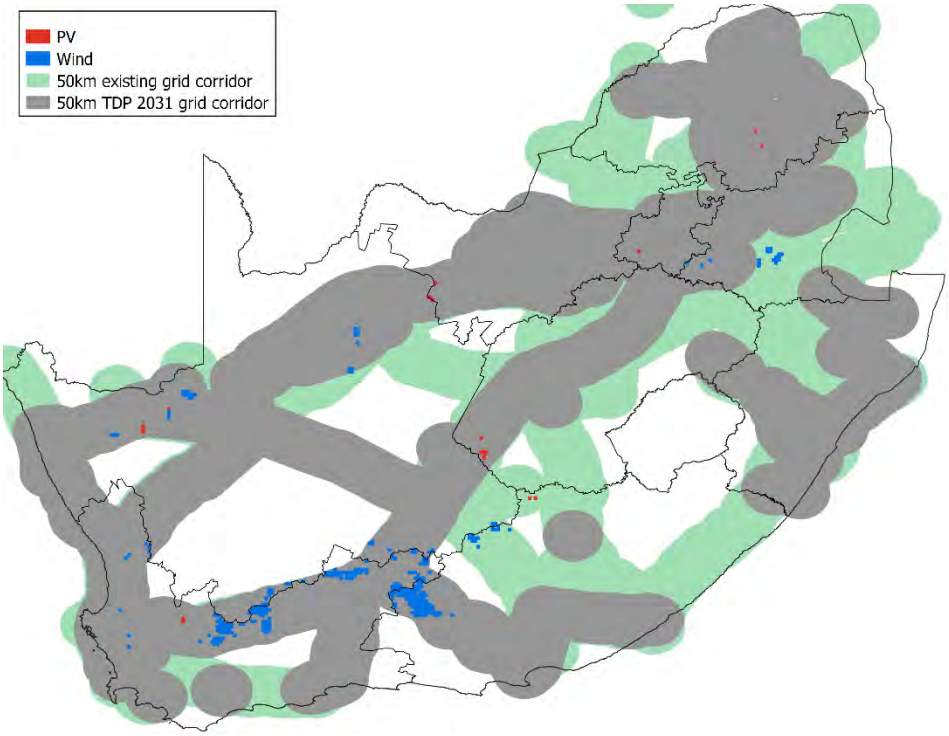


Figure 59 Scenario 1 (with IRP Province constraints), Stage 2 (with reallocation based on grid proximity considerations): transmission lines, grid proximity corridors, substations, and re-allocated Elementary Units for localizing V-RES.

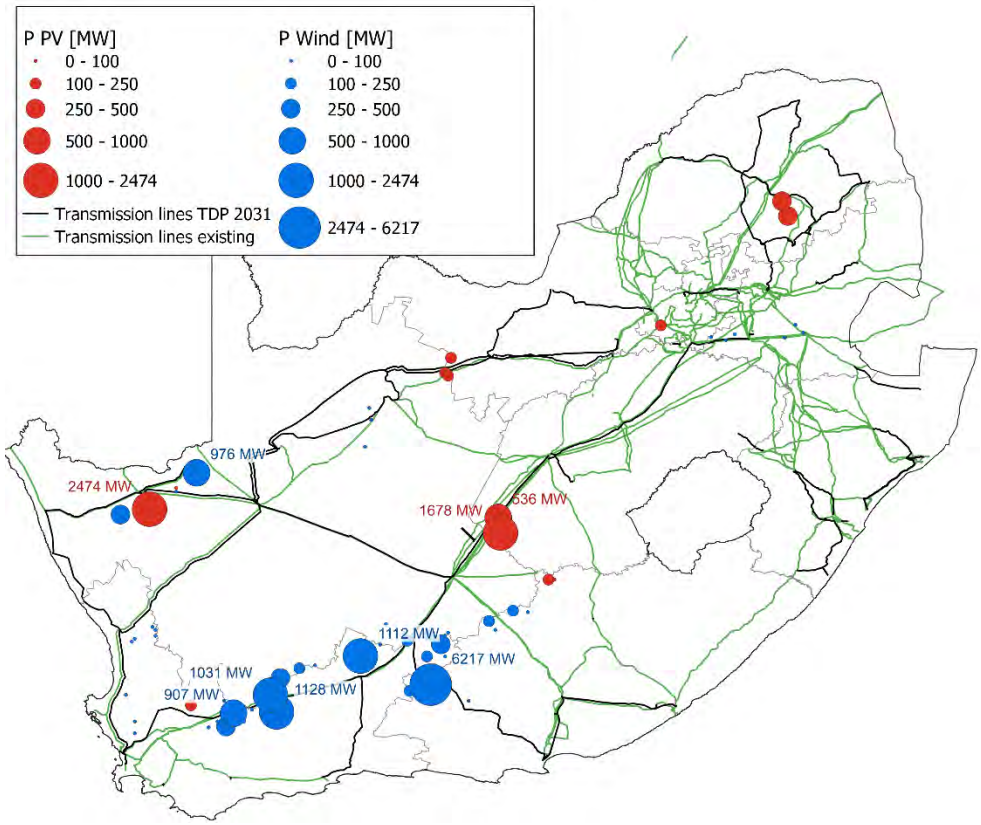


Figure 60 Scenario 1 (with IRP Province constraints), Stage 2 (with reallocation based on grid proximity considerations): re-allocated capacities of localized V-REs.

Table 23 Results of Scenario 1 (with IRP Province constraints), Stage 2 (with reallocation based on grid proximity considerations).

	Solar PV				Wind			
Provinces	**P [MW]**	**LCOE [$/MWh]**	**Energy [GWh]**	**Area [km²]**	**P [MW]**	**LCOE [$/MWh]**	**Energy [GWh]**	**Area [km²]**
Eastern Cape	131	44.0	252	3.1	5868	33.2	24974	1047
Free State	2214	44.0	4244	53.0	0	0.0	0	
Gauteng	151	46.2	276	3.6	0	0.0	0	
KwaZulu-Natal	0	0.0	0	0.0	0	0.0	0	
Limpopo	535	46.3	975	12.8	0	0.0	0	
Mpumalanga	0	0.0	0	0.0	351.5	36.1	1374	63
Northern Cape	2557	41.7	5170	61.2	2182	29.6	10397	
North West	632	43.8	1219	15.1	0	0.0	0	377
Western Cape	244	43.4	475	5.8	6313	31.5	28335	1108
TOT	**6464**	**43.2**	**12609**	**154.7**	**14715**	**31.9**	**65080**	**2595**

With respect to the results of the Scenario 1 derived in Stage 1 (i.e., without grid proximity considerations), the re-allocation within each Province leads to almost negligible differences in terms of Max yearly energy producible [TWh] (around 0% and 1% lower for solar and wind, respectively) and Average LCOE [$/MWh] (around 0% and 2% higher for solar and wind, respectively), confirming that guiding V-RES localization within the least-cost Elementary Units within a 50 km-corridor surrounding the existing and planned grid is still a near-optimal allocation that minimizes the average LCOE.

Moving to the *Stage 3: Considerations on grid impact*, the results achieved so far with Stage 2 allow to provide preliminary insights to Eskom on the possible areas where the grid (existing and planned) may deserve more attention through detailed power system study to assess the impact on V-RES installation on such areas. As preliminary step, Figure 61 reports the re-allocated (<50 km) capacities of localized V-RES as grouped in three different clusters, according to their expected level of impact on the grid. The level of impact has been estimated based on the following two criteria:

1) Whether the new plants are expected to connect to the existing portions of the grid/substations or the new planned ones.
2) The estimated level of congestion in the different Provinces, according to the Generation Connection Capacity Assessment (GCCA) 2024[9] (Figure 62), which gives information on readily accessible generation connection capacity within the network, incorporating all the bid windows up to round BidW5.

The following 3 clusters have been identified:

1) *Cluster 1 (red), expected high impact:* it includes four (4) groups of V-RES installations:
    a. The 3.9 GW group in the north-west area of Northern Cape, composed by around 2.4 GW of solar PV and 1.5 GW of wind. In the whole Northern Cape, 0 GW of connection capacity is readily accessible (Figure 62), but relevant grid reinforcements are expected as per TDP 231 (black lines in Figure 61). Nevertheless, given such large amount of capacity that is expected to be connected in that portion of the line, a proper grid impact assessment is suggested.

[9] https://www.eskom.co.za/eskom-divisions/tx/gcca/. Accessed: September 2022.

b. The 5.1 GW group (mainly wind) on the line at the border between Northern Cape and Western Cape, and the 7.3 GW group (all wind) on the line at the border between Western Cape and Eastern Cape. According to the GCCA, the connection capacity readily accessible in the two Capes (Figure 62) is not sufficient to host the new expected connections, but relevant grid reinforcements are expected as per TDP 231 (black lines in Figure 61). Nevertheless, given such large amount of capacity that is expected to be connected in those two lines, a proper grid impact assessment is suggested.
c. The 5.6 GW group (only solar) on the corridor in Free State. According to the GCCA, the connection capacity readily accessible in the Province is higher than 4 GW (Figure 62), but is not sufficient to host the new expected connections. Again, relevant grid reinforcements are expected as per TDP 231 (black lines in Figure 61) but, given such large amount of capacity that is expected to be connected in those two lines, a proper grid impact assessment is suggested.

2) *Cluster 2 (orange), expected medium impact:* it includes three (3) groups of V-RES installations:
   a. The 0.6 GW group (solar) on the corridor at the border between Northern Cape and North West, which may be affected by the null connection capacity readily accessible (Figure 62) Northern Cape, but a relevant double-lines reinforcement is expected as per TDP 231 (black lines in Figure 61).
3) *Cluster 3 (green), expected low impact:* all the remaining groups where the expected connection capacity is well below the readily accessible connection capacity in the Provinces, as per GCCA (Figure 62), and grid reinforcement are expected as per TDP 2031.

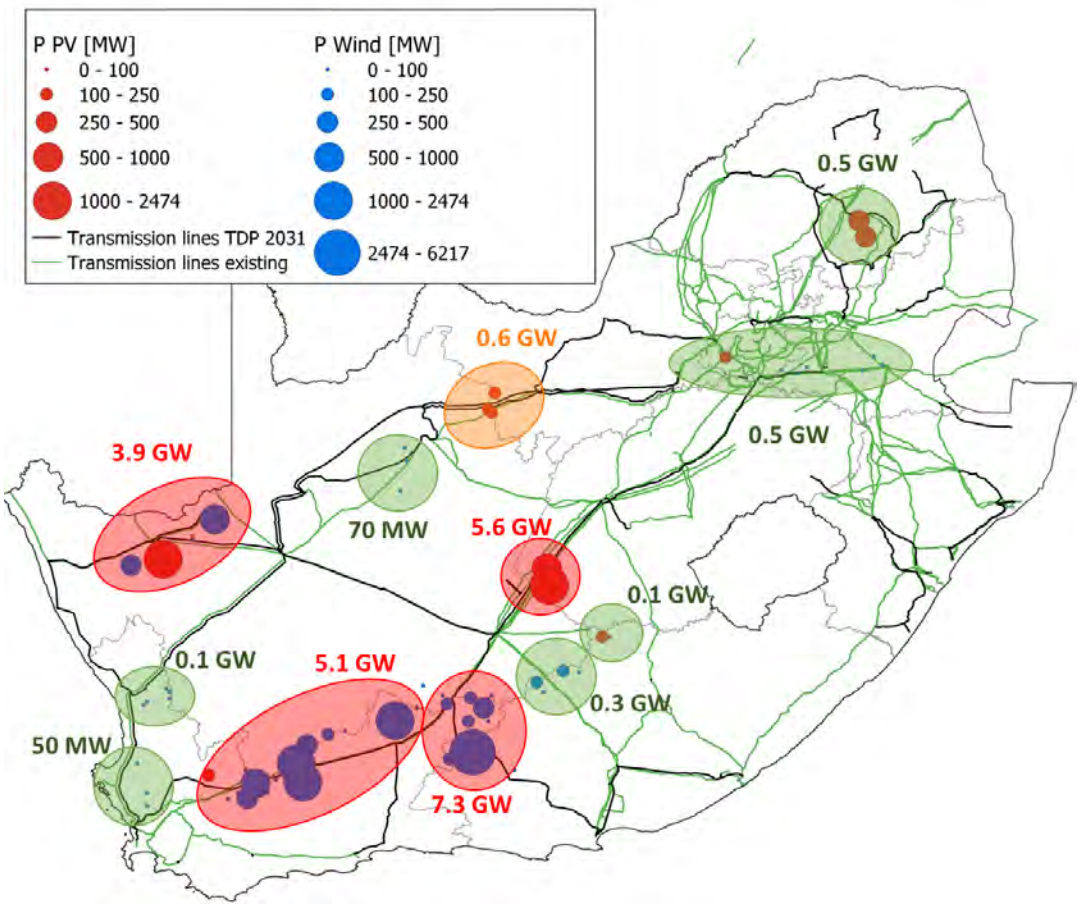


Figure 61 Clusters of re-allocated capacities of localized V-REs.

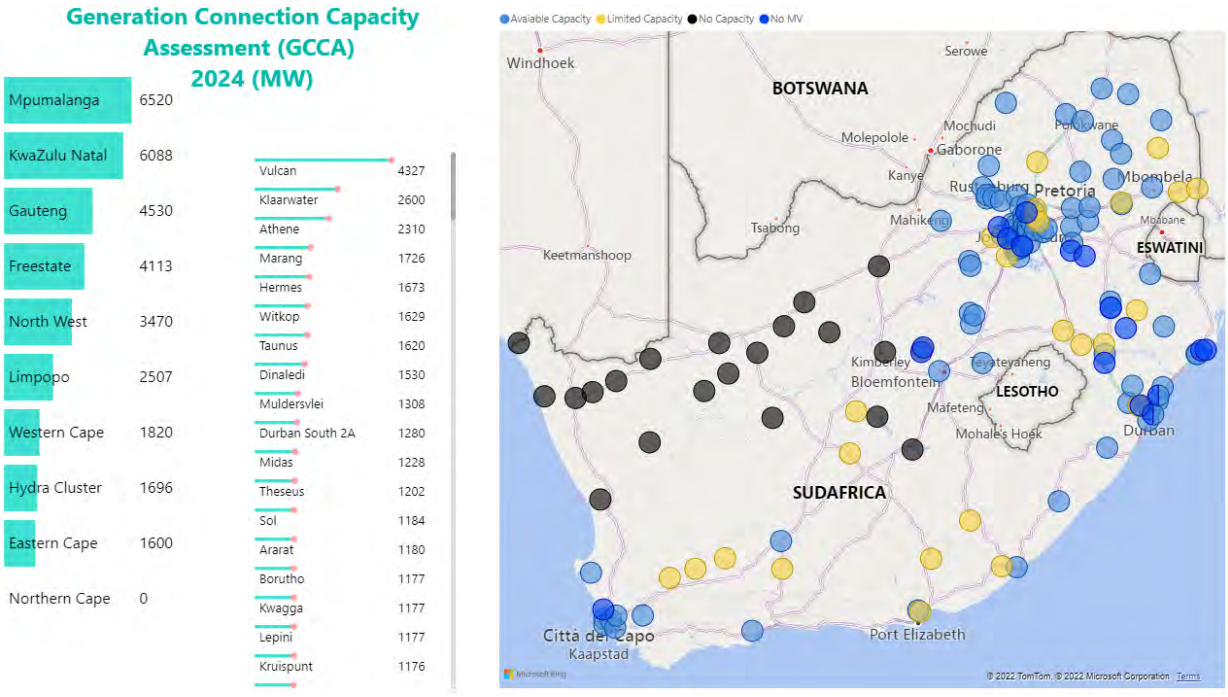


Figure 62 Grid Connection Capacity Assessment (GCCA) 2024 Transmission network.

Finally, results of *Stage 4: Evaluation of RES installations cost-opportunity* are reported. Figure 63 shows the amount of total capacity for solar and wind reallocated in the North-Eastern area[10]. The LCOE obtained with these hypotheses is then compared to the LCOE of Scenario 1 to evaluate the cost difference and consequently the breakeven cost for infrastructure reinforcements in the West-East corridor that would make the two solutions equivalents, net of the possible minor reinforcements that are anyhow necessary for accommodating a massive V-RES plants in the North-East area.



Figure 63 North-East reallocation with total energy production from Scenario 1: installed capacities of V-RES.

Table 24 Cost comparison between Scenario 1 (with IRP Province constraints) and the Scenario with North-East reallocation. This table is subject to sensitivity analysis in Section 8 (Ⓢ).

	LCOE Scenario 1 [$/MWh]	LCOE Scenario w/ North-East Reallocation [$/MWh]	Delta LCOE %	Differential cost (cost-opportunity for Grid expansion) [M$][11]
PV	43.2	45.6	5%	288
Wind	31.5	42.9	36%	7275
TOT	33.4	43.3	30%	7563

The following considerations can be drawn:

[10] As explained in the methodology (Section 7.5.2), to be conservative, the analysis investigated the extreme case: even in case the equivalent area in North-East necessary for covering the required energy production is higher than the effective Admissible area therein, the remaining capacity is supposed to still be allocated at the same expected LCOE and CF as the mean capacity already re-allocated.

[11] This value has been calculated by multiplying the same total expected energy production of the two Scenarios (i.e., around 78.2 TWh/year for 30 years) by the difference of the average LCOEs of the two Scenarios.

- The Delta LCOE for wind is considerably larger than the one for solar. This indicates that investing in grid expansion/reinforcing for evacuating wind production is more lucrative compared to solar.
- The differential cost over a horizon of 30 years between the two scenarios is of around 7.5 billion USD. Considering this value as a proxy for the cost-opportunity to invest in transmission grid expansion of the West-East corridors, this suggests that as long as the cost for reinforcing the infrastructure in the South-West area and the interconnection towards the load centres is significantly below this number, it may be worth to prioritize the Western areas with lowest LCOE for installing V-RES plants.
- The previous 7.5 billion figure should be intended as the order of magnitude of the actual cost-opportunity to be further adopted in eventual strategic planning decisions. In fact, deeper cost-benefit and financial analyses, which are out of the scope of this study, should be taken into consideration in order to include also the following factors that may have and incremental (+) or decremental (-) impact of that figure:
    - (+) Given the massive quantity of V-RES plants reallocated in the North-East area, possible (minor) reinforcements also in that area may emerge.
    - (+) This scenario looks at the TDP2031 capacity target up to 2030, which is only 10 years ahead and that represents an intermediate milestone towards the full decarbonization of the South African system. By considering the new targets of the TDP2022 (26.4 GW of wind and 18.3 GW of solar by 2032), but also by looking at V-RES integration as a long-term target (e.g., 2050), it clearly emerges that the localization of V-RES cannot preclude the Western region of the country, confirming the need for network development in that area and the West-East corridor.
    - (-) The analysis has been done with the LCOE calculated at Step 4, which considers the present technology costs. Since the costs for PV and wind are expected to decrease in the year, this effect is expected to diminish the differential cost between the two Scenarios (optimal least-cost allocation in Western areas vs North-East reallocation).

Moreover, based on the data on the Admissible areas of the SEA study provide by Eskom, it emerges that the surface areas requirements for wind installations make it impossible to entirely move the wind production in the North-East (Figure 64). Also, it is worth mentioning that load centres are also present in the West part of the country, especially in the South. These two aspects emphasise the needs for grid reinforcements for the West-East corridor even in the Reallocated Scenario.

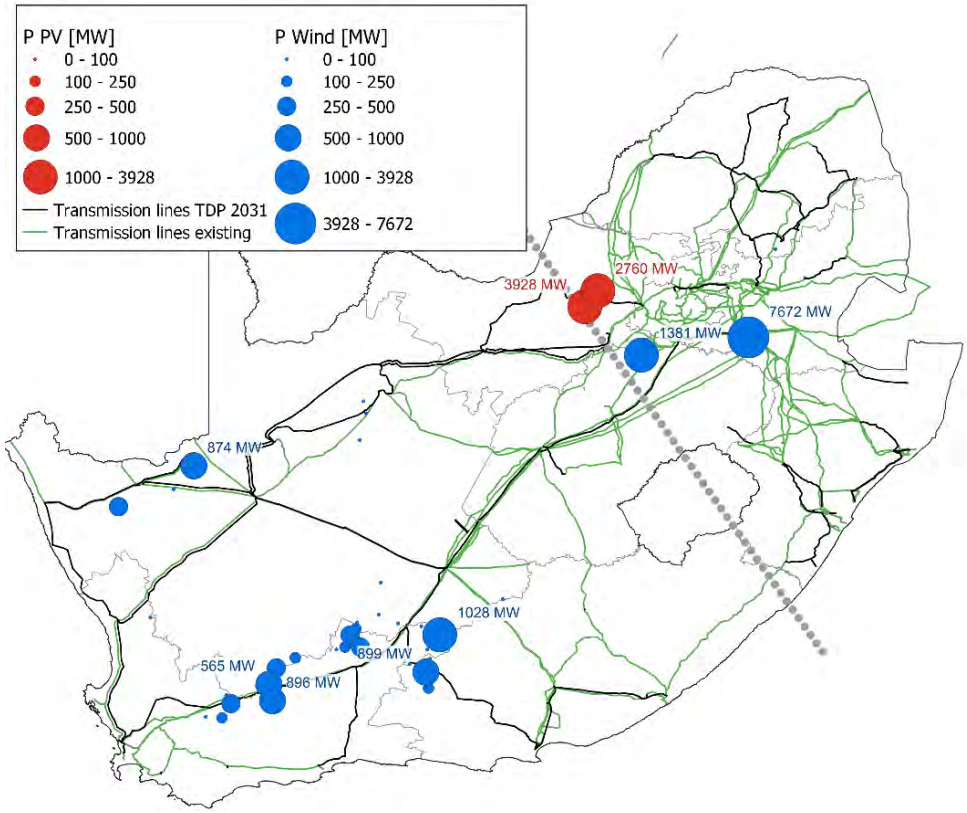


Figure 64 North-East reallocation with also the constraint on the Admissible areas: installed capacities of localized V-RES.

7.6.2 Results (Part 2)

Table 25 summarizes the key data regarding the renewable generation and costs in 2021 and for the REIPPPP BidW5 and the results derived from Part 1 of this Step 6 (see Table 21). The table allows a quick comparison between costs and the quantities involved.

Table 25 Summary of key data on renewables generation and costs.

Reference year / future installations	MW	GWh	$/MWh
2021 - all renewables	5 761	15 208	146.4
REIPPPP BidW5 - Wind	1 608	7 169	33.5
REIPPPP BidW5 - Solar PV	975	1 902	29.2
New potential as per Table 21 - Wind	14 715	65 961	31.5 (Ⓢ)
New potential as per Table 21 - Solar PV	6 464	12 613	43.2 (Ⓢ)
TOTAL / Weighted average for cost	**29 523**	**102 853**	**50.0** (Ⓢ)

Overall, the commissioning of all the capacity that awarded a fully indexed tariff from REIPPPP BidW5 and of all the new expected capacity would lead to a substantial decrease in the total weighted average supply costs from renewable IPPs for Eskom: from the 146.4 $/MWh of 2021 (based on the latest available data from the Eskom Integrated Report 2021) to around 50 $/MWh (Ⓢ). The potential decrease in the Renewables IPP supply costs for Eskom is projected to happen from 2021 to 2031, when the new capacity should be commissioned. This should, other things being equal, bring about a reduction (or at least a stabilization) of the energy component of the MEGAFlex tariff.

The impact of this expected decrease of the Renewables IPP supply costs on the total supply costs of electricity for Eskom will depend on the total electricity demand, total generation by source, and supply costs for all the non-renewable sources in 2031, which is out of the scope of this activity. Nevertheless, based on the results of optimal V-RES generation obtained in this study, it is possible to state that a gradual replacement of coal generation by V-RES generation will decrease the cost of supply: according to the data provided by Eskom, the electricity demand should increase from 227 TWh of 2021 up to 259 TWh in 2031, while in the meantime V-RES generation should increase from a total of 15.2 TWh in 2021 to more than 102 TWh in 2031 (see Table 25). This evolution of the system would lower the residual room for covering demand from non-renewable sources from 212 TWh in 2021 to 156 TWh in 2031, resulting in a potential displacement of coal generation caused by V-RESs of up to 56 TWh[12]. Considering the 2031 horizon, the recent trends in South African coal cost and the current and expected international market trend for coal prices, a substantial increase in the costs of coal are expected in the following years: the variable electricity supply cost for Eskom from coal for 2031 estimated by CESI is 79 $/MWh, significatively higher that the LCOE for wind and solar PV, with the result that that exploiting V-RES generation for substituting coal generation (part of) by 2031 will lead to a decrease in the in the supply costs for Eskom. Not to mention the effect of "unavailability" of the existing coal power plants, which is expected to worsen in the next years due to the aging of the current conventional generation fleet and therefore to reinforce the conclusion on the positive impact of V-RES on decreasing the generation supply cost in South Africa.

To have a more complete picture on how this reduction of supply costs of V-RES electricity generation could impact the electricity tariffs for final consumers, some further elements need to be considered:

- From today to 2031 wind and solar PV costs are likely to keep on decreasing, so that the actual LCOE of the new installations from today to 2031 can be lower. Renewables are therefore expected to become more and more competitive.
- Renewables variable generation cost tend to be stable over time once the investment is done, while with fossil fuelled thermal generation (such as coal) the variable costs can be very volatile as linked to the fossil fuels global markets and geopolitical circumstances. This aspect has been considered in the analysis by estimating a potential increment of cost for coal, but steeper increments cannot be excluded. On the contrary, renewables entail more price stability (lower price risks) for Eskom and the final consumers.
- In the next few years, the carbon tax related costs will finally have to be borne by Eskom[13]. Considering an average efficiency of coal power plants of 35% and an emission factor for coal of 0.35 tCO2/MWh, a CO2 price of 10 $/tCO2 would result in 10.6 $/MWh of additional costs for generating each MWh with coal, while with 50 $/tCO2 the additional coasts would be 53.2 $/MWh[14].

In conclusion, from an overall energy-balance point of view, the impact of V-RES penetration on the total variable supply cost for Eskom and on the energy component of the tariffs is expected to be positive in the long term (decreasing variable costs and tariffs). If fossil fuels prices will increase substantially and/or a significative Carbon Tax will be applied to the fossil fuelled generation of Eskom, V-RES generation will most likely be much cheaper than the traditional thermal generation.

[12] With the hypothesis that V-RES will first replace, among all non-renewable resources, coal generation.

[13] https://www.eskom.co.za/eskom-updates-key-assumptions-in-the-revenue-requirement-for-fy-2024-and-fy-2025/

[14] Currently the CO2 spot prices European Union Allowance (EUA) under the European Union Emissions Trading Scheme (EU ETS) are between 60 and 70 €/tCO2.

In the next years the renewable generation could be the part of the generation which will allow to keep the average variable supply cost of electricity and the related tariff to final consumers under control, providing price stability and avoiding strong increases.

8. SENSITIVITY ANALYSIS Ⓢ

This Section aims at testing the impact of the most sensitive parameters used in this study on the relevant results. The sensitivity analysis is performed after a discussion with RES4Africa, based on their experience in the South African energy context, which proposed the following new set of inputs:

<table>
<tr><th>Parameter</th><th>PV</th><th>Wind</th></tr>
<tr><td>Land occupation</td><td>-33% (1.6 ha/MW)

Based on the experience of RES4Africa (through developers) in South Africa.</td><td>-</td></tr>
<tr><td>CF/Energy Yield, scale-up factor</td><td>+23%

To test bifacial modules combined with tracking system based on the experience of RES4Africa (through developers) in South Africa.</td><td><table><tr><th></th><th>Avg. Scale-factor</th></tr><tr><td>Eastern Cape</td><td>-15%</td></tr><tr><td>Free State</td><td>-28%</td></tr><tr><td>Gauteng</td><td>-27%</td></tr><tr><td>KwaZulu-Natal</td><td>-14%</td></tr><tr><td>Limpopo</td><td>-46%</td></tr><tr><td>Mpumalanga</td><td>-23%</td></tr><tr><td>Northern Cape</td><td>-17%</td></tr><tr><td>North West</td><td>-23%</td></tr><tr><td>Western Cape</td><td>-18%</td></tr><tr><td>TOT Average</td><td>-18%</td></tr></table>
To smooth the differences with the ESMAP Global Wind Atlas and based on the experience of RES4Africa (through developers) in South Africa.</td></tr>
<tr><td>CAPEX</td><td>-9% (ca. 676 – 780 $/kW)

To test bifacial modules combined with tracking system based on the experience of RES4Africa (through developers) in South Africa.</td><td>-7% (ca. 936 – 1248 $/kW)

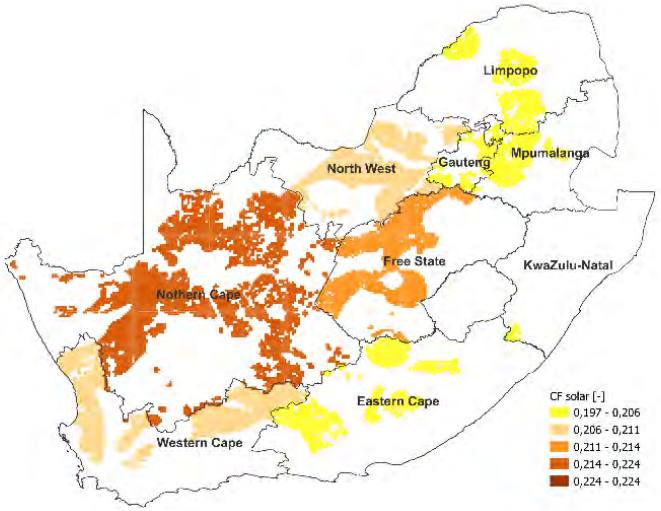
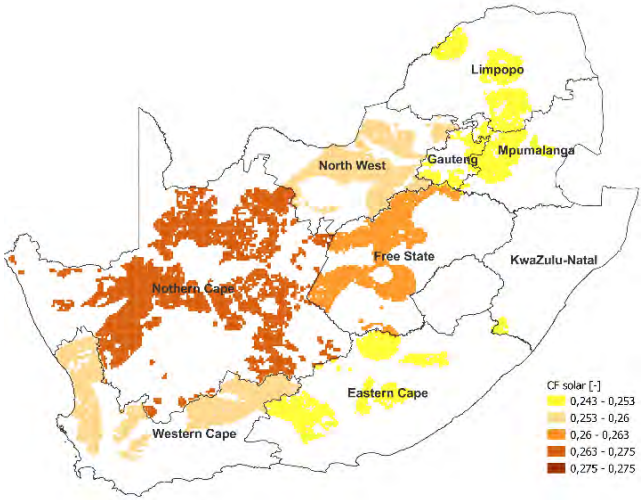
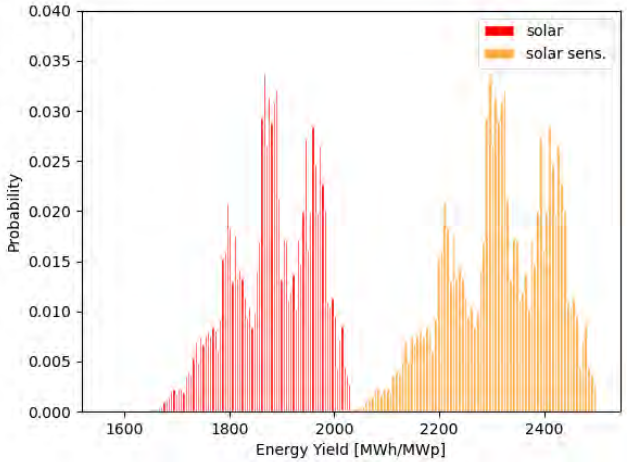
Based on the experience of RES4Africa (through developers) in South Africa.</td></tr>
<tr><td>OPEX</td><td>+58% (ca. 15 $/kW/year)

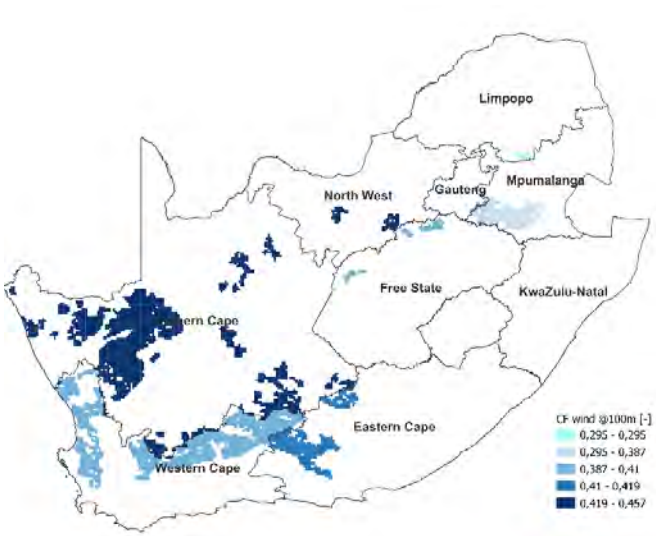
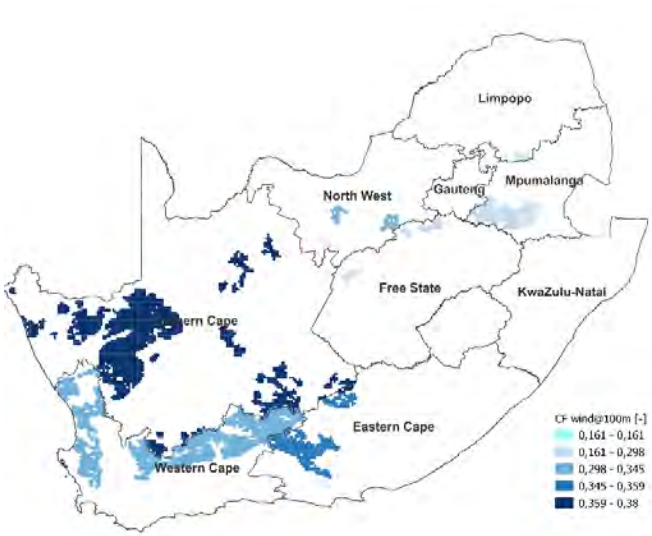
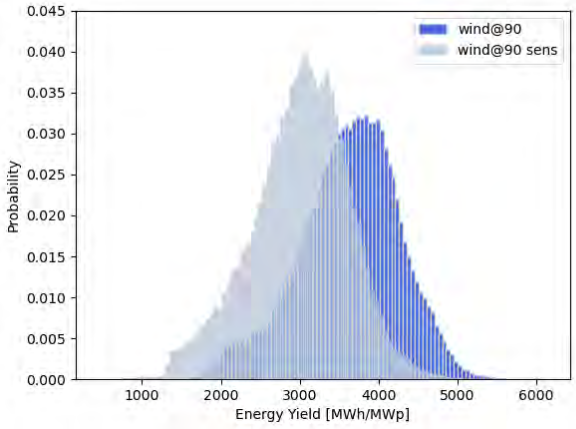
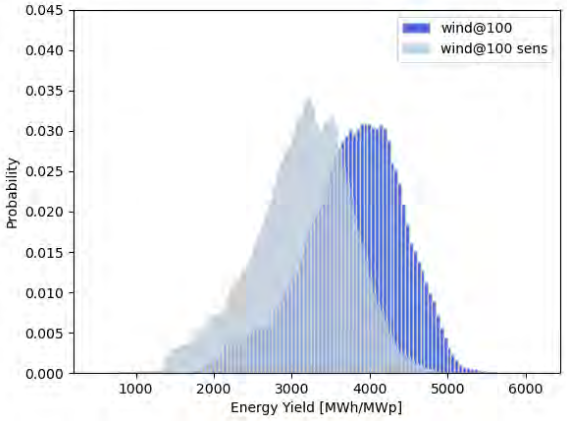
To test bifacial modules combined with tracking system based on the experience of RES4Africa (through developers) in South Africa.</td><td>-8%/-46% (ca. 25 $/kW/year)

Based on the experience of RES4Africa (through developers) in South Africa.</td></tr>
<tr><td>Project Lifetime</td><td>-</td><td>25 years

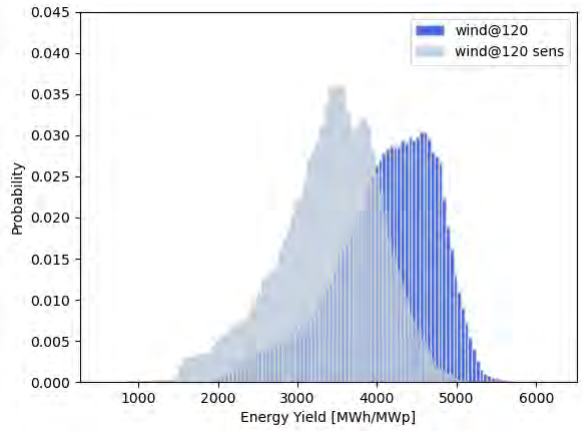
Based on the experience of RES4Africa (through developers) in South Africa.</td></tr>
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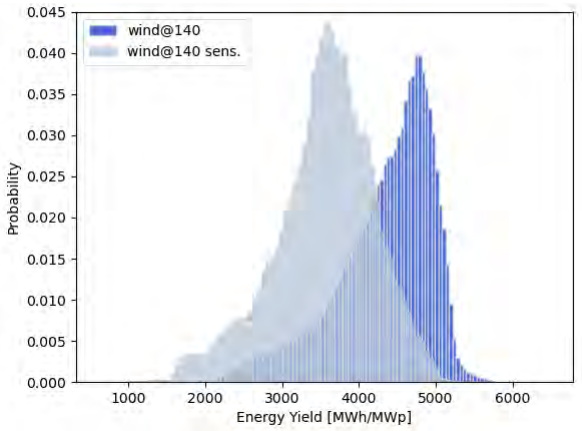
Based on these new inputs, simulations are performed from Step 2 to Step 6, providing the results reported in the next tables.

BEFORE Sensitivity	AFTER Sensitivity	Discussion
STEP 2/3		
		The average Provincial CF of solar PV after the sensitivity analysis is, coherently with the adopted assumption, 23% higher than the value before sensitivity. It ranges from 0.240 (around 2100 equivalent hours) in KwaZulu-Natal up to 0.275 (2400 equivalent hours) in Northern Cape. This represents the expected average energy yield of bifacial PV with tracking system.
		The histogram shows a comparison of the probability distribution of Energy Yield (i.e., equivalent hours) values before (red) and after (yellow) the sensitivity. The two graphs, shifted by a factor of 1.23, do not overlap in any range of the Energy Yield, meaning that PV plants with tracking systems installed in the least promising areas are in any case producing more than fixed axis systems installed in the spots with highest availability of the solar resource.

BEFORE Sensitivity	AFTER Sensitivity	Discussion
STEP 2/3		
		The sensitivity analysis leads to a reduction of average provincial wind CF in all the Provinces, ranging from a minimum of 0.161 (1410 equivalent hours) in Limpopo (which is the region with less wind resource in both cases) to a maximum of 0.380 in Northern Cape (3300 equivalent hours), the region with highest average CF in both cases.
		The histograms show a comparison between the probability distribution of the energy yield (i.e., equivalent hours) across South Africa before (dark blue) and after the sensitivity (light blue) at the 4 analysed hub heights (90 m, 100 m, 120 m, 140 m). In all the cases the curve after the sensitivity is shifted towards the left, i.e., at lower values of energy yield. The differences are more marked at 140 m.

BEFORE Sensitivity	AFTER Sensitivity	Discussion
STEP 2/3		



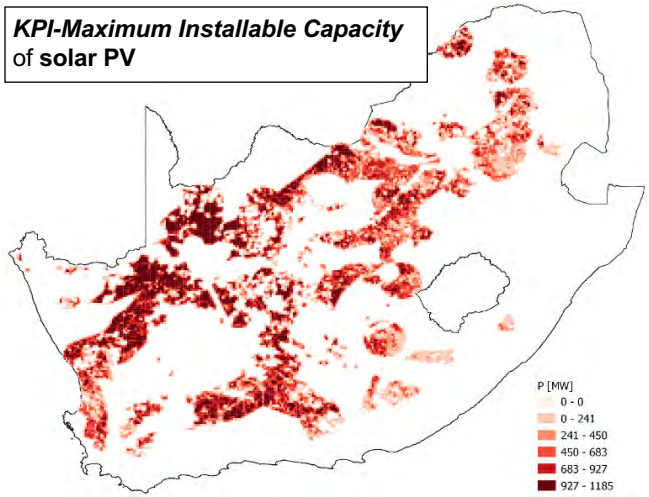
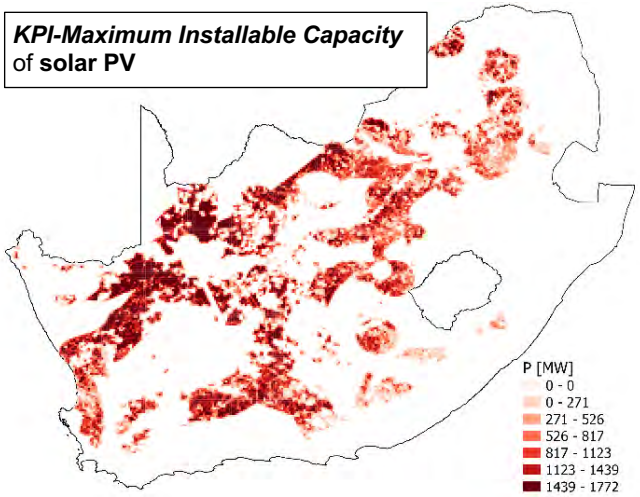
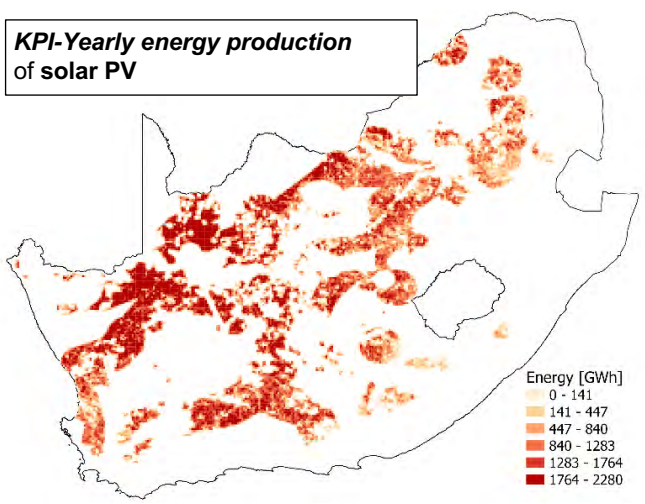
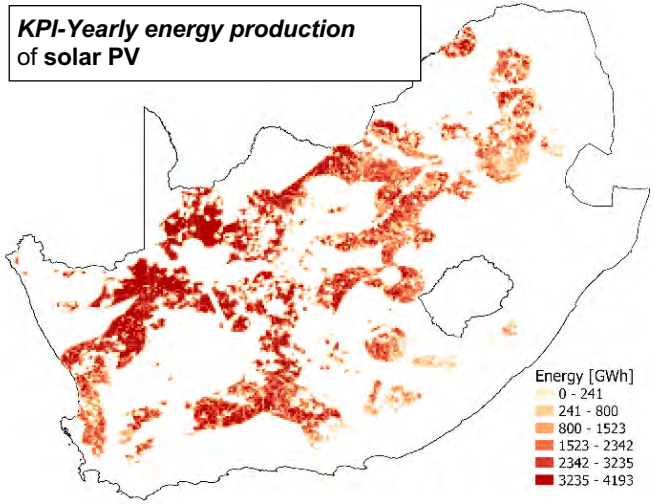


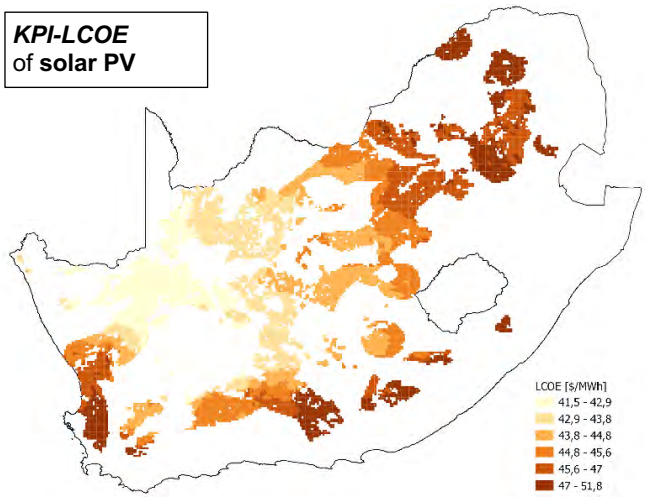
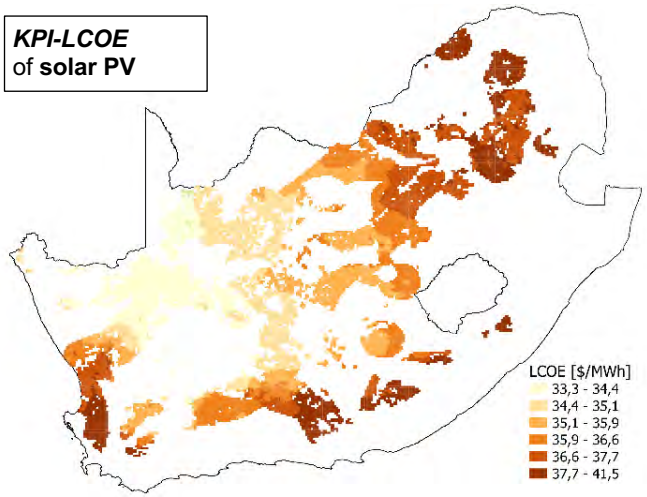
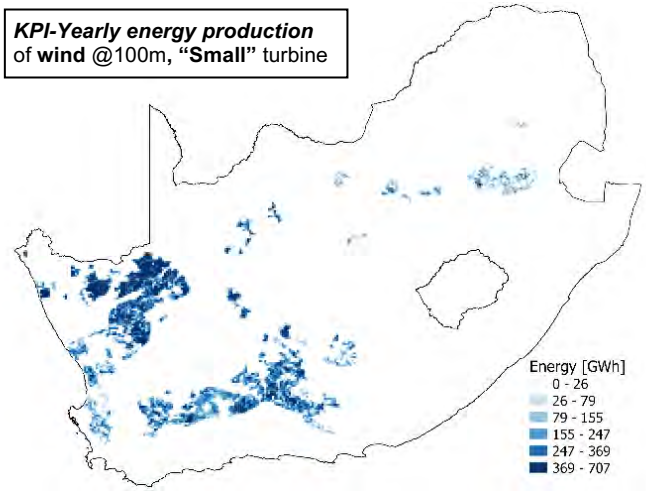
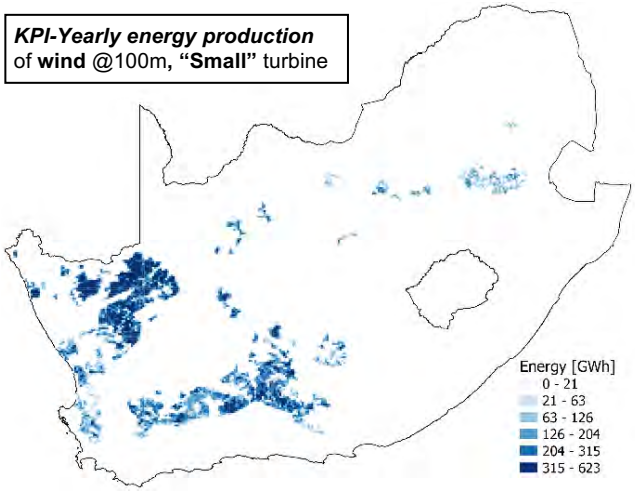
Provinces	Avg. PV CF	Avg. Wind CF @90 m	Avg. Wind CF @100m	Avg. Wind CF @120 m	Avg. Wind CF @140 m
Eastern Cape	0.21	0.4	0.42	0.45	0.48
Free State	0.21	0.39	0.41	0.45	0.49
Gauteng	0.21	0.39	0.41	0.45	0.48
KwaZulu-Natal	0.20	0.33	0.35	0.38	0.41
Limpopo	0.20	0.28	0.29	0.33	0.35
Mpumalanga	0.20	0.37	0.39	0.43	0.46
Northern Cape	0.22	0.44	0.46	0.50	0.53
North West	0.21	0.39	0.43	0.49	0.52
Western Cape	0.21	0.39	0.40	0.43	0.46

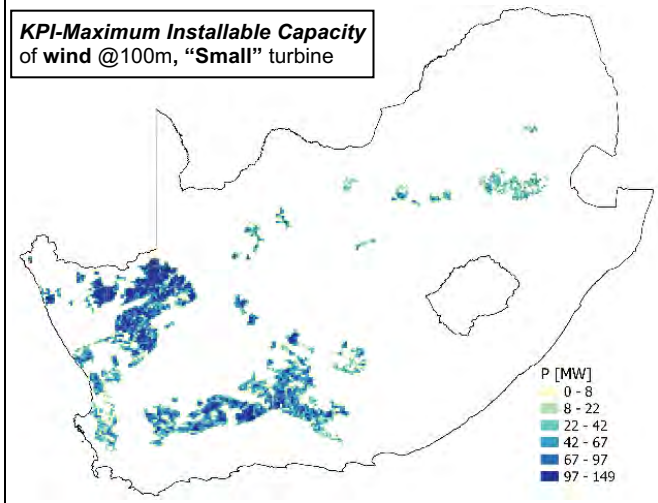
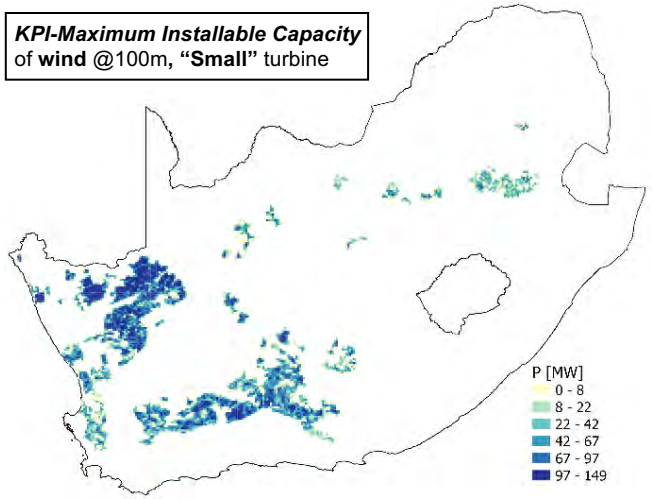
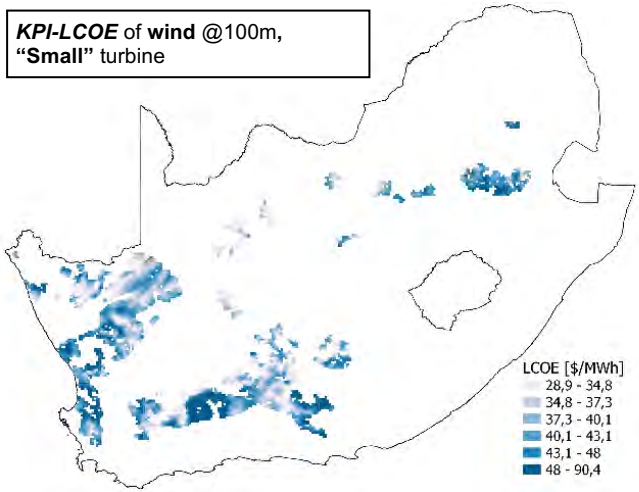
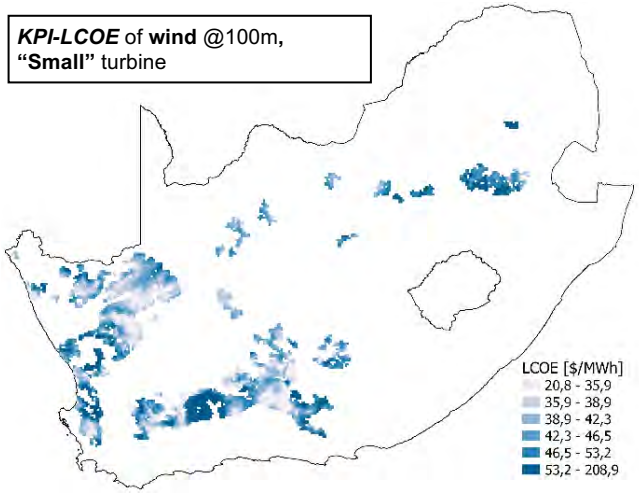
Provinces	Avg. PV CF	Avg. Wind CF @90 m	Avg. Wind CF @100m	Avg. Wind CF @120 m	Avg. Wind CF @140 m
Eastern Cape	0.25	0.35	0.36	0.39	0.40
Free State	0.26	0.28	0.30	0.33	0.35
Gauteng	0.25	0.28	0.30	0.33	0.35
KwaZulu-Natal	0.24	0.28	0.30	0.33	0.35
Limpopo	0.25	0.15	0.16	0.18	0.19
Mpumalanga	0.25	0.28	0.30	0.33	0.36
Northern Cape	0.28	0.36	0.38	0.41	0.43
North West	0.26	0.33	0.34	0.38	0.40
Western Cape	0.26	0.32	0.33	0.36	0.38

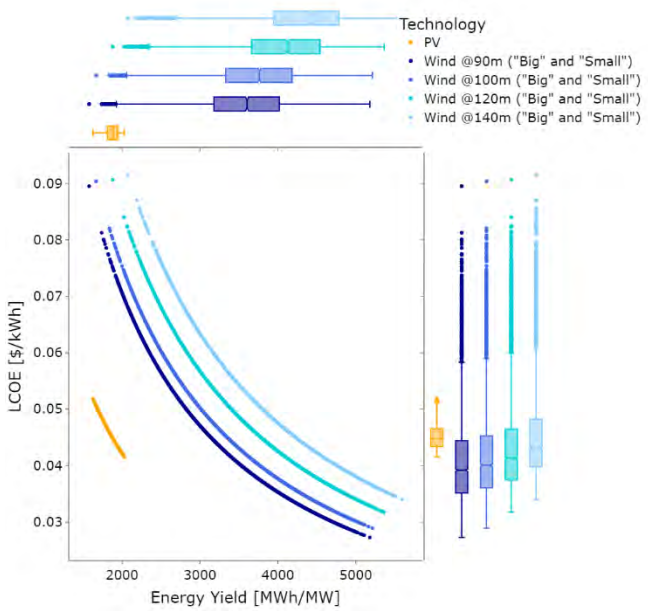
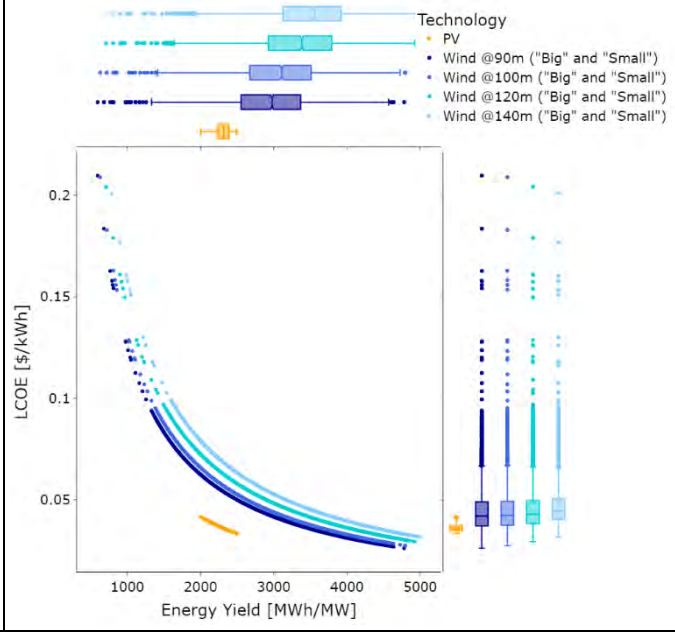
The tables report values for the average provincial CF before and after the sensitivity. The colours in the table on the right (after the sensitivity) highlight the relative difference of the CFs after the sensitivity with respect to the original values. Green gradation is where the CF increases after the sensitivity (i.e., for solar), the yellow-orange-red gradation refer to the cases of decrease in CF.

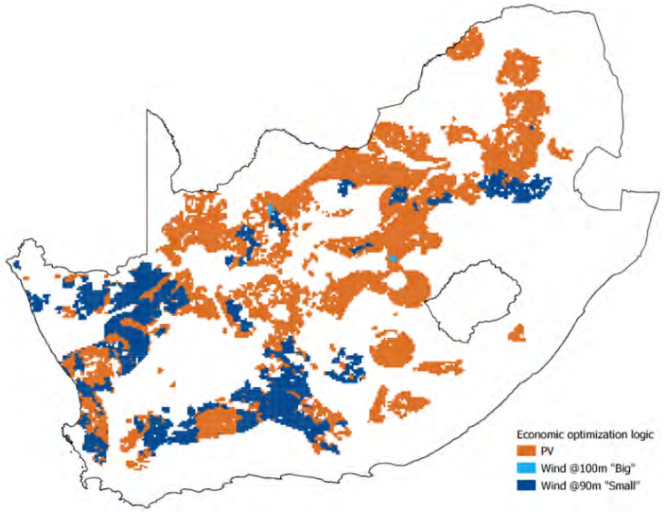
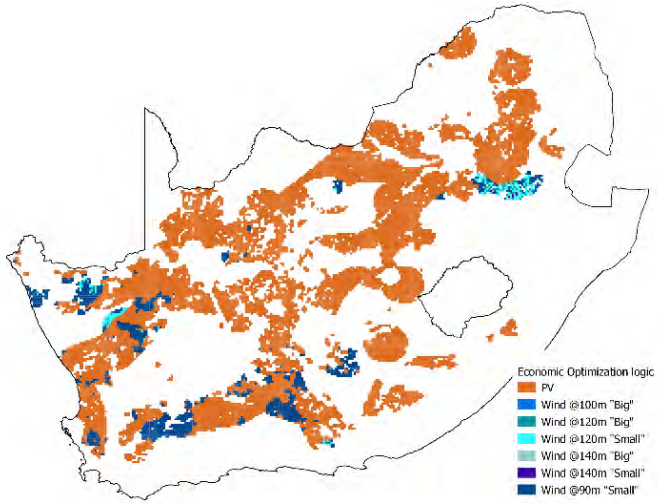
It appears that Limpopo is the Province where the wind CFs are subject to the deepest decrease.

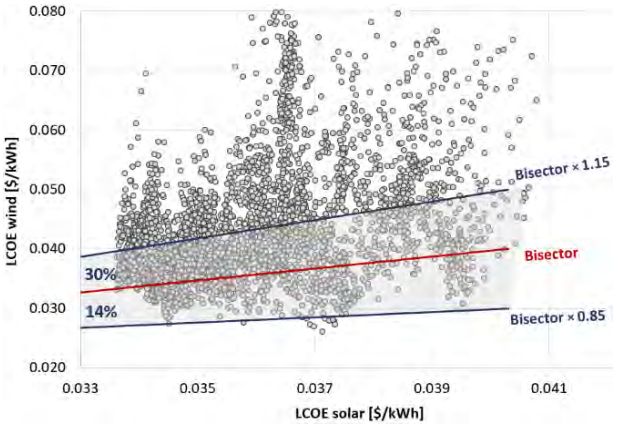
BEFORE Sensitivity	AFTER Sensitivity	Discussion
STEP 4		
		The increase of KPI-Maximum Installable Capacity in each Elementary Unit after the sensitivity analysis is related to the reduction of the land occupation of PV farms (from 2.4 ha/MW to 1.6 ha/MW). With the new value of land occupation, there are Elementary Units that are expected to allocate more than 1.77 GW (with respect to the previously 1.18 GW).
		The maps show the KPI-Yearly Energy Production in each Elementary Unit. The values almost double after the sensitivity (max of 4193 GWh after the sensitivity with respect to a max of 2280 GWh before sensitivity) because of the concurrent effects of the decrease of the land occupation of PV plants and the increase of their CF.

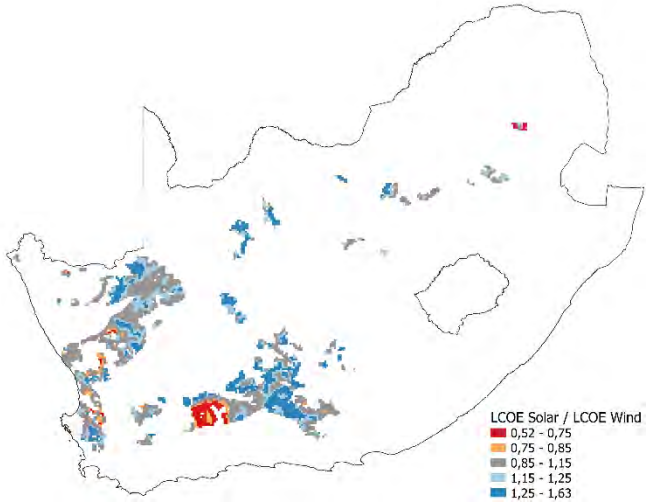
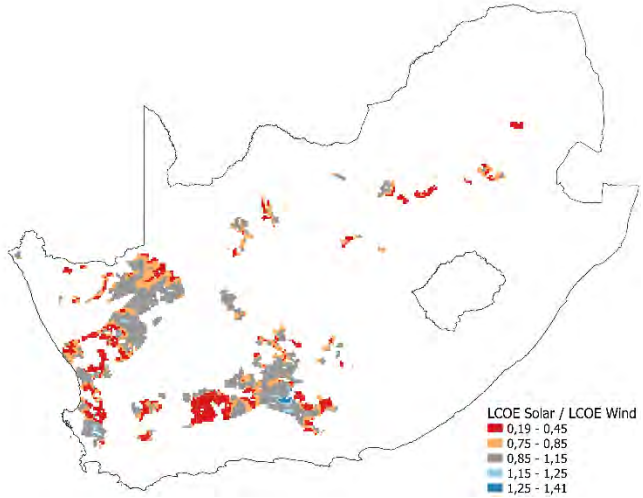
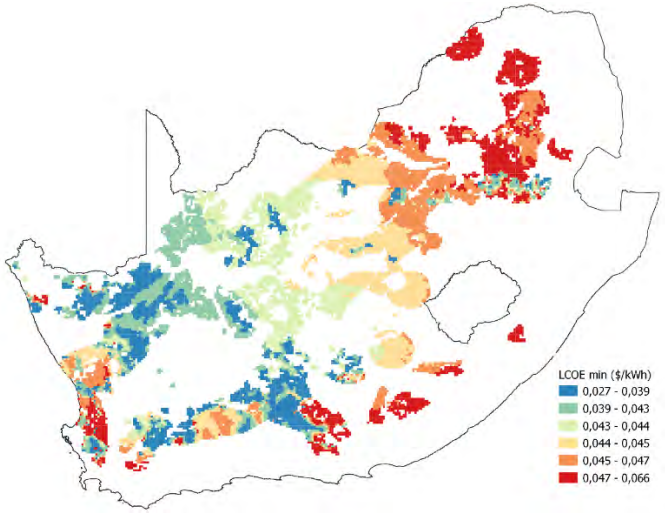
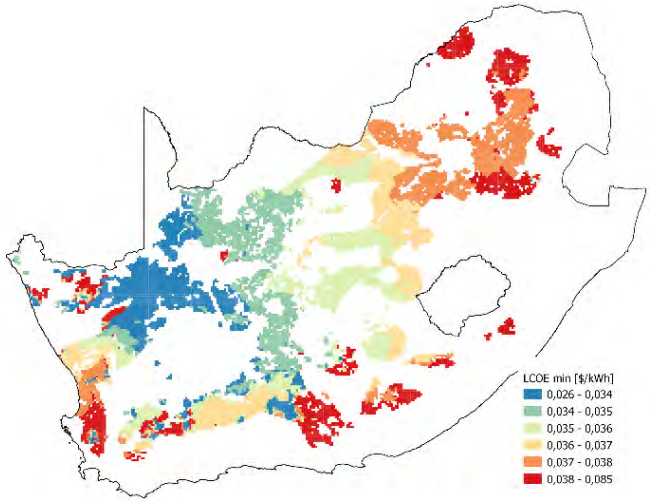
BEFORE Sensitivity	AFTER Sensitivity	Discussion
STEP 4		
KPI-LCOE of **solar PV** 	***KPI-LCOE*** of **solar PV** 	The decrease of KPI-LCOE after the sensitivity is a consequence of the increase of energy yield (the two values are inversely proportional) and the reduction of CAPEX, which, combined, are able to offset the increase in OPEX. LCOE passes from a range of 41.5 $/MWh-51.8 $/MWh to 33.3 $/MWh in the most promising areas of Northern Cape up to 41.5 $/MWh in Limpopo and Mpumalanga Provinces.
KPI-Yearly energy production of **wind** @100m, **"Small"** turbine 	***KPI-Yearly energy production*** of **wind** @100m, **"Small"** turbine 	The reduction of the KPI-Yearly Energy Production in 99% of the Elementary units is a consequence of the reduction of the CF/Energy Yield discussed above. The difference of energy production ranges from +12% up to -62%.

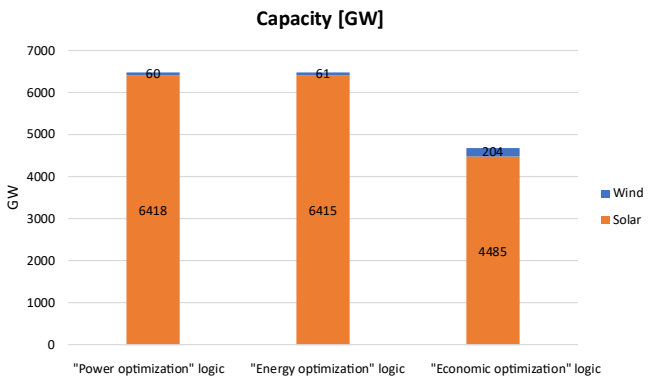
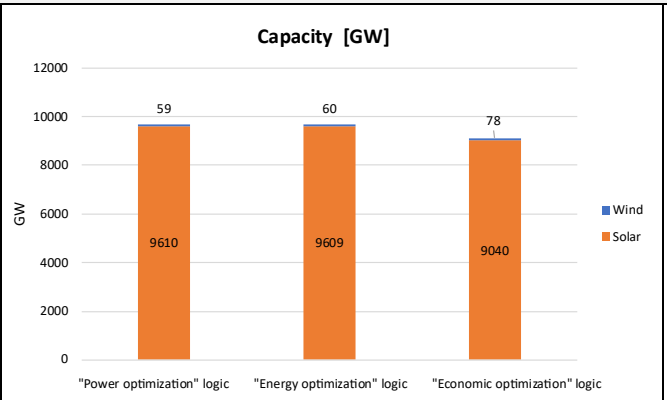
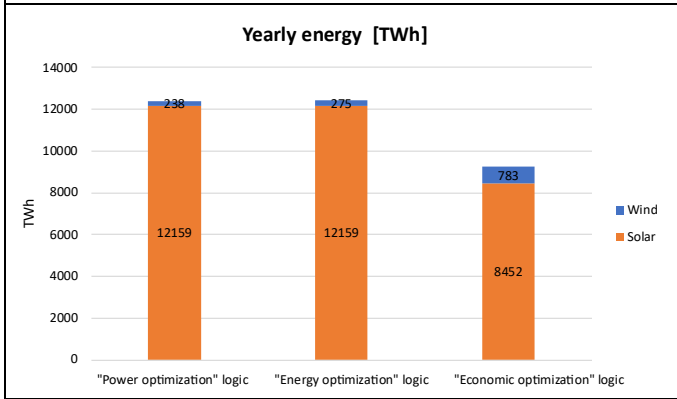
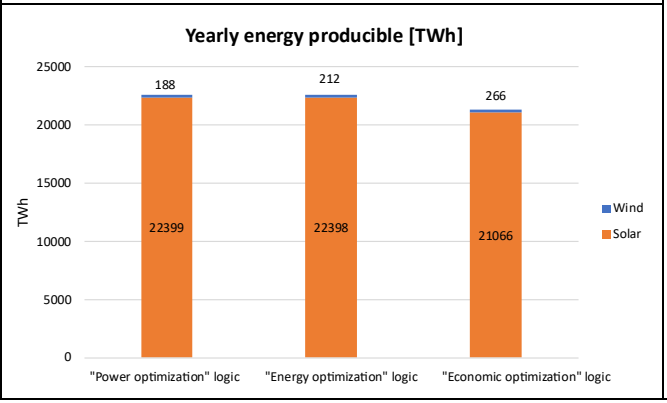
BEFORE Sensitivity	AFTER Sensitivity	Discussion
STEP 4		
		The KPI-Maximum Installable Capacity in each Elementary Unit does not change after the sensitivity since the wind turbines land occupation was not a parameter subject to sensitivity.
		The delta in the KPI-LCOE before and after the sensitivity is the result of the concurrent effects of the increase of wind CAPEX and OPEX, the increase of the wind turbines useful life, and the reduction of CF. Around 3 fourths of the Elementary Units experience an increase of the LCOE, while around 1 fourth (26%) show a decrease of the LCOE, where the reduction in costs and increase of useful life offsets the lower capacity factor.

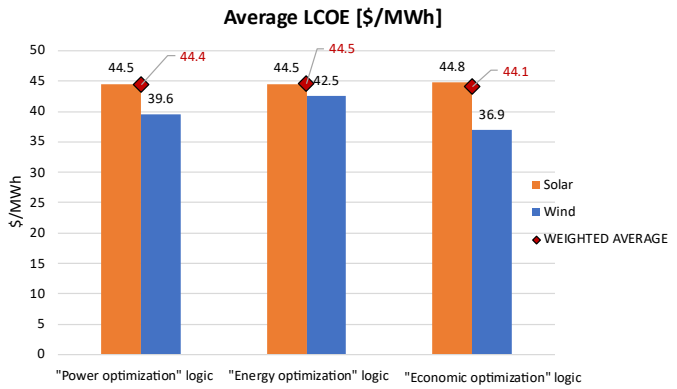
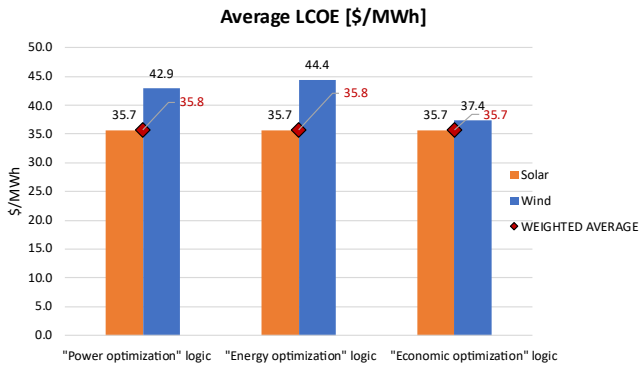
BEFORE Sensitivity	AFTER Sensitivity	Discussion
STEP 4		
		The scatter plots show the correlation between the LCOE, and the Energy Yield of the technologies considered. From a pure economic point of view, solar PV (bifacial with tracking), after the sensitivity, is cheaper than wind up to almost 3’000 equivalent hours, where wind and solar LCOE ranges start overlapping.

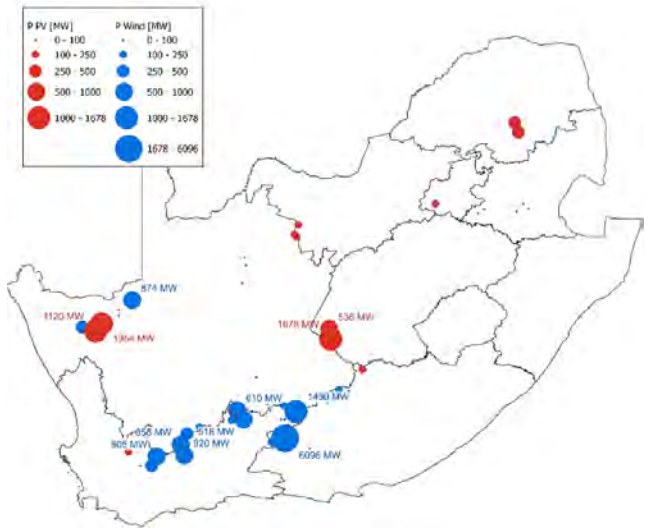
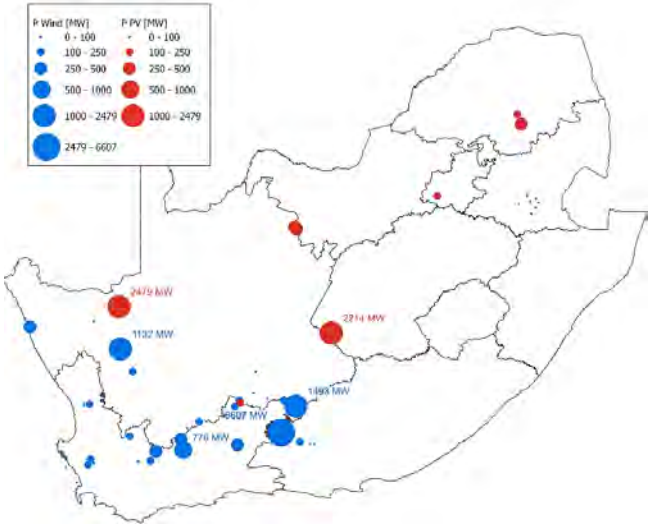
BEFORE Sensitivity	AFTER Sensitivity	Discussion
STEP 5		
The figure shall be intended as an "**optionality**" V-RES graph: for each Elementary Unit, it is only meant to provide the V-RES option with the lowest average LCOE. It shall **not lead** to the conclusion that one V-RES shall be privileged with respect to the other. 		These maps report the result of the optimal PV-wind allocation in the Admissible areas based on the Economic Optimization logic. As expected, from a pure economic standpoint, the areas where wind results to be more competitive than solar are lower due to new sensitivity parameters. This reflects also in a lower "optimal" capacity allocation for wind after sensitivity (78 GW) with respect to the same value before sensitivity (204 GW). It should be considered that being the analysis performed in Step 5 a pure numerical optimization, it provides only a binary result (i.e., wind vs PV for each cell). For this reason, the figure shall not necessarily lead to a conclusion that PV shall be privileged to wind in the South African territory. To confirm this, next figure reports a scatter plot with the LCOE values for of wind vs the LCOE of PV in the Admissible areas where both wind and PV may be installed.

BEFORE Sensitivity	AFTER Sensitivity	Discussion
	STEP 5	
		 As displayed, 44% of the dots falls within the ±15% band around the bisector, meaning that for almost half of the 5x5 km^2 areas, the affordability of one source respect the other is very similar. From the standpoint of a wind developer, this means that the allocation of wind reported in the map do not represent an upper limit to the opportunities for investing in affordable wind installations with respect to solar PV.
		This figure reports the ratio between the LCOE solar and LCOE wind in the areas where both wind and solar can be installed, colouring in grey the areas where the two LCOEs vary of less than ± 15%.

BEFORE Sensitivity	AFTER Sensitivity	Discussion
STEP 5		
		Also in the sensitivity case, most of the territory falls within this grey band, meaning that the affordability of one source respect the other is very similar in those areas. With respect to the main case, the remaining-coloured areas are predominantly reddish, meaning that solar can reach lower LCOE values respect to wind in those areas.
		These figures report the LCOE maps obtained through the allocation performed with the Economic Optimisation criterion. The same considerations as for the previous maps can be drawn: after the sensitivity, PV results to be allocated in more Elementary Units, leading to more uniformly distributed areas with lower LCOEs. This emerges clearly in Northern Cape and part in the Western Cape.

BEFORE Sensitivity	AFTER Sensitivity	Discussion
STEP 5		
		***NB**: this figure reports the resuming results concerning the 3 KPIs (i.e., KPI-Maximum Installable Capacity, KPI-Yearly energy production, KPI-LCOE) based on the "optionality" V-RES graphs performed with the 3 optimization logics. They are meant to provide the cumulated values of the 3 KPIs obtained by selecting in every single Elementary Unit the optimal V-RES according to each optimization criterion. The numbers **do not** represent upper physical limits to the installation of one V-RES with respect to the other.*
		The figures report the summary results of the optimizations performed with the 3 different criteria. About the sensitivity graphs (on the right): - Concerning the Capacity [GW] graph, the results really impacted are the ones obtained with the Economic optimization logic. This leads to the previously discussed lower "optimal" capacity allocation for wind after

BEFORE Sensitivity	AFTER Sensitivity	Discussion
STEP 5		
		sensitivity (78 GW) with respect to the same value before sensitivity (204 GW). - Concerning the Yearly energy [TWh] graph, all the 3 optimization logics lead to less favorable results for wind. This is mainly due to the lower CFs of wind and higher CFs for solar PV tested in the sensitivity analysis. - Concerning the Average LCOE [$/MWh], the results invert the positioning of solar PV with respect to wind, resulting to be cheaper, on average. In turn, this effect impacts positively the average LCOE, which reduces from 44.1 $/MWh up to 35.7 $/MWh.

BEFORE Sensitivity	AFTER Sensitivity	Discussion
STEP 6		
		The maps localize the target capacities of the plants in the Elementary Units of the different Provinces, with the details reported in the tables below. After the sensitivity, the following main considerations can be drawn: • *Solar PV* benefits everywhere from lower LCOE values and higher expected output, due to lower CAPEX and more efficient technology. The optimal localization does not considerably deviate with respect to the original case, apart from the fact that the target capacities are more concentrated in fewer areas due to the lower land occupation. • *Wind* reveals not homogeneous results. Eastern Cape is the only Province with lower LCOE values. On average, the global country LCOE does not really differs in the two cases. All the Province experience lower expected output, due to lower tested CFs. This leads to a sensible difference in the optimal localization of the target capacity, which results to be also more sparsely distributed in the territory.

	Solar PV			
Provinces	P [MW]	LCOE [$/MWh]	Energy [GWh]	Area [km²]
Eastern Cape	131	44.0	252	3.1
Free State	2214	44.0	4244	53.0
Gauteng	151	46.2	276	3.6
KwaZulu-Natal	0	0.0	0	0.0
Limpopo	535	46.3	975	12.8
Mpumalanga	0	0.0	0	0.0
Northern Cape	2557	41.7	5173	61.2
North West	632	43.8	1219	15.1
Western Cape	244	43.3	475	5.8
TOT	**6464**	**43.2**	**12613**	**154.7**

	Wind			
Provinces	P [MW]	LCOE [$/MWh]	Energy [GWh]	Area [km²]

	Solar PV			
Provinces	P [MW]	LCOE [$/MWh]	Energy [GWh]	Area [km²]
Eastern Cape	131	35.2	311	2.1
Free State	2214	35.3	5222	35.4
Gauteng	151	37.0	339	2.4
KwaZulu-Natal	0	0.0	0	0.0
Limpopo	535	37.1	1199	8.6
Mpumalanga	0	0.0	0	0.0
Northern Cape	2557	33.3	6382	40.9
North West	632	35.1	1499	10.1
Western Cape	244	34.3	592	3.9
TOT	**6464**	**34.6**	**15545**	**103.4**

	Wind

BEFORE Sensitivity	AFTER Sensitivity	Discussion

STEP 6

Eastern Cape	5868	33.2	24980	1047
Free State	0	0.0	0	0
Gauteng	0	0.0	0	0
KwaZulu-Natal	0	0.0	0	0
Limpopo	0	0.0	0	0
Mpumalanga	351.5	36.1	1374	63
Northern Cape	2182	29.6	10412	376
North West	0	0.0	0	0
Western Cape	6313	30.5	29194	1086
TOT	**14715**	**31.5**	**65961**	**2573**

Provinces	P [MW]	LCOE [$/MWh]	Energy [GWh]	Area [km^2]
Eastern Cape	5868	32.0	22892	1049
Free State	0	0.0	0	0
Gauteng	0	0.0	0	0
KwaZulu-Natal	0	0.0	0	0
Limpopo	0	0.0	0	0
Mpumalanga	351.5	37.4	1181	62
Northern Cape	2182	29.7	9163	383
North West	0	0.0	0	0
Western Cape	6313	31.6	24956	1088
TOT	**14715**	**31.6**	**58193**	**2582**

	LCOE Scenario 1 [$/MWh]	LCOE Scenario w/ North-East Reallocation [$/MWh]	Delta LCOE %	Differential cost [M$]
PV	43.2	45.6	5%	288
Wind	31.5	42.9	36%	7275
TOT	33.4	43.3	30%	**7563**

	LCOE Scenario 1 [$/MWh]	LCOE Scenario w/ North-East Reallocation [$/MWh]	Delta LCOE %	Differential cost [M$]
PV	34.6	36.5	6%	289
Wind	31.6	49.4	56%	10106
TOT	32.2	46.7	45%	**10395**

The tables report the results of the North-East reallocation to assess the opportunity cost for grid reinforcement.
The differential cost increases from 7.5 billion $ to 10.3 billion $, as a result of the reduced efficiency of the wind plants, which decreases relatively more in the North-East areas than in the Western part of the country.

Total weighted average supply costs from renewable IPPs for Eskom: around 50.03 $/MWh	Total weighted average supply costs from renewable IPPs for Eskom: around 49.98 $/MWh	The difference is negligible (less than 1%)

9. CONCLUSIONS AND FURTHER STEPS

This study reports all the assumptions, steps, results, and outcomes of the "Integration of Non-Programmable Renewable Energy in the National Electric System of South Africa" aimed at providing the relevant stakeholders with all the necessary elements to identify the **actual value of V-RES (i.e., solar PV and wind) in South Africa in accordance with Potential, Exploitability, Economics, Viability and Impact criteria**.

As agreed with RES4Africa and also shared with Eskom, the quantitative assessment of the impact of the results, in terms of massive implementation of the V-RES onto the identified locations of the grid, on the security of supply and operation of the South African Transmission Grid are excluded from the analysis, since they would require appropriate adequacy and network studies that are out of the scope of the analysis.

The main outcomes of the study in terms of V-RES value are reported below, together with an excursus on the main assumptions underlying the calculations through the different Steps of the study. The items in brackets "(Ⓢ)" refer to the quantitative hypotheses tested in the sensitivity analysis, and the related results.

Potential

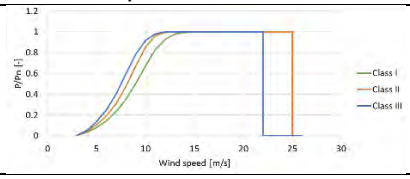
Solar and wind potential is estimated in the Admissible Areas identified in the SEA report, that consider environmental, social, and technical constraints to limit RES installation only in some circumscribed areas of the whole South African territory. The following data sources have been considered:

Parameter	PV	Source	Wind	Source
GHI	Raster map	Global Solar Atlas [1]	n/a	n/a
GTI	Raster map	Global Solar Atlas [1]	n/a	n/a
Wind speed	n/a	n/a	Raster map	WASA [2]
Weibull A	n/a	n/a	Raster map	WASA [2]
Weibull k	n/a	n/a	Raster map	WASA [2]
Admissible areas	Vector map	ESKOM	Vector map	ESKOM

Solar irradiation is well distributed across the country, providing large solar potential with average values of GTI among 6 to 7 kWh/m^2/day, which place South Africa among the countries with the highest radiation levels in the world. The Province with the largest solar potential is Northern Cape, which is also the region with the largest (in absolute terms) territory that may host solar fields, according to the Admissible areas identified in the SEA study.
Concerning wind, average values of wind speed around 7/8 m/s at 100 m make wind availability in South Africa comparable to the Northern Continental European countries. The Admissible areas for wind resource are limited mainly to the Northern and Western Capes. Moreover, with respect to solar, wind availability is much less uniformly distributed in the areas, ranging from locations where the average wind speed exceeds 12 m/s up to locations characterized by much lower values, close to 4 m/s.

Exploitability

The exploitability of V-RES has been calculated first as CF and Energy Yield, and then translated in terms of optimized maximum capacity and producible energy with high spatial resolution (5x5 km^2). The following hypotheses on the main parameters have been considered:

<table>
<tr><th>Parameter</th><th>PV</th><th>Source</th><th>Wind</th><th>Source</th></tr>
<tr><td>Technology</td><td>Monofacial PV without tracking (Ⓢ Bifacial PV with tracking)</td><td>n/a</td><td>
<table>
<tr><th colspan="5">Turbine types</th></tr>
<tr><td>Nominal Power</td><td>4.7</td><td>5</td><td>6.6</td><td>6.6</td></tr>
<tr><td>Turbine Diameter [m]</td><td>155</td><td>145</td><td>170</td><td>155</td></tr>
<tr><td></td><td colspan="2">“Small”</td><td colspan="2">“Big”</td></tr>
<tr><td>Wind Class</td><td>Class III</td><td>Class I- II</td><td>Class III</td><td>Class I- II</td></tr>
</table>
</td><td>n/a</td></tr>
<tr><td>CF/Energy Yield</td><td>Raster map (Ⓢ +23%)</td><td>Global Solar Atlas [1]</td><td>calculated (Ⓢ -18%, on average)</td><td>n/a</td></tr>
<tr><td>Weibull A</td><td>n/a</td><td>n/a</td><td>Raster map</td><td>WASA [2]</td></tr>
<tr><td>Weibull k</td><td>n/a</td><td>n/a</td><td>Raster map</td><td>WASA [2]</td></tr>
<tr><td>Power curves</td><td>n/a</td><td>n/a</td><td>
</td><td>NREL [3]</td></tr>
<tr><td>Land occupation</td><td>2.4 ha/MW (Ⓢ 1.6 ha/MW)</td><td>SEA Study [7] + CESI assumptions</td><td>5Dx7D</td><td>SEA study</td></tr>
</table>

The resources availability reflects into the large technical potential of photovoltaics, from 1700 to 2000 yearly equivalent hours (Ⓢ 2100 to 2400), and wind, from 2000 to 5500 yearly equivalent hours (Ⓢ 1400 to 5000), evaluated at different heights and for different wind classes. The two most attractive Provinces for V-RES installations (both wind and solar), considering both the available Admissible areas and the V-RES potential, are Northern Cape and Western Cape, followed by Free State (mainly solar), North West (mainly solar), Eastern Cape (both wind and solar), and Limpopo (mainly solar). Those are the Provinces where it would be possible to install most of the solar and wind capacity, reaching the highest values of yearly energy produced.

PV plants occupy less area per MW with respect to wind plants: 2.4 ha/MW (Ⓢ 1.6 ha/MW) against around 20 ha/MW according to the assumptions considered. For this reason, in the Admissible areas where both wind and PV plants could be deployed, PV is the optimized solution when either the capacity installable or the energy produced wants to be maximized, despite the lower energy yield. The maximum V-RES capacity that could be theoretically installed in the country if all the Admissible areas where used is around 6400 GW (Ⓢ 9700 GW) and the maximum energy producible is around 12’000 TWh (Ⓢ 22’000 TWh), hundreds of times higher than the current energy needs.

Economics

LCOE is computed for monofacial photovoltaics crystalline modules without tracking and wind technologies at different hub heights and sizes of turbines, based on the following additional hypotheses:

Parameter	PV	Source	Wind	Source
CAPEX	800 $/kW (Ⓢ ca 676 – 780 $/kW)	Lazard [8]	Dependent on hub height (Ⓢ)	SAWEA + NREL [9]
OPEX	9.5 $/kW/year (Ⓢ ca. 15 $/kW/year)	Lazard [8]	2.7% of CAPEX (Ⓢ ca. 25 $/kW/year)	Lazard [8]

Parameter	PV	Source	Wind	Source
WACC	0.096	Lazard [8]	0.096	Lazard [8]
Project Lifetime	30 years	Lazard [8]	20 years (Ⓢ 25 years)	Lazard [8]

The results on the LCOE range from around 50 $/kWh to around 40 $/kWh (Ⓢ 33 $/kWh to around 41 $/kWh) for PV plants against a range of 90 $/kWh to 30 $/kWh (Ⓢ 200 $/kWh to 21 $/kWh) in the case of wind plants. This variability is a consequence of the distribution of the energy yield for the two resources, more homogeneous for PV than wind. In case of wind, the LCOE increases with the hub height of the turbines, showing that the higher energy production exploitable at higher altitudes does not necessary compensate the higher costs faced for the installation of taller turbines. Those values are strongly impacted by the cost assumptions and the assumptions on the discount factor, which, although in line with literature LCOE values, could be more conservative with respect to real life conditions faced by RES developers, thus explaining the lower cost of latest REIPPPP bids. Optimizing wind and PV integration to minimize the total LCOE of new installations, it is wind that is selected in most of the Admissible areas where both technologies could be installed. According to this economic optimization, LCOE in the country would range from a minimum of 27 $/MWh (Ⓢ 26 $/MWh) in the North Cape and Western Cape provinces to a maximum of 66 $/MWh (Ⓢ 85 $/MWh) in the north-eastern part of the country.

Viability

The investigation of optimal location for V-RES installations is performed according to two different scenarios of V-RES penetration, according to the TDP2021, with or without respecting IRP constraints related to Provinces' allocations, with a least-cost merit order logic. It shall be noted that the latest *TDP2022* (covering the 2023-2032 period), published concurrently to the finalization of this study, substantially increases the target quantities of V-RES in 2031 in South Africa but it is not expected to report conclusions that may impact on the hypotheses and outcomes of this study. In the further steps, an update of the viability-outcomes is suggested to align the results with the new V-RES targets.

Following IRP allocation, Western Cape is the Province that is expected to allocate the largest area for V-RES, mainly wind farms, and it turns out to be the Province with the highest V-RES capacity penetration, with around 6.5 GW. Eastern Cape follows, with almost 6 GW of wind plants localized in the north of the Province. The expected capacity of solar PV is almost equally split between Free State (around 2.2 GW) and Northern Cape (around 2.5 GW). The relaxation of the IRP Province-boundary constraint leads to a less distributed localization of V-RES, concentrating in areas with lowest LCOE, mainly located in Northern Cape. Nevertheless, the effective benefits of constraints relaxation in terms of decrease in LCOE and increase of energy production are negligible. Also, the re-allocation within each Province of V-RES in 50km existing grid corridors, less critical from the power system point of view, leads to almost negligible differences in terms of decrease of energy producible and average LCOE. It is demonstrated that there is room for allocating V-RES in low-cost areas, while also considering the current grid congestion challenges that the South African power system is experiencing. For example, in case a more disaggregate V-RES distribution within or among provinces could avoid worsening or could even improve the power system condition, areas with slightly higher LCOE could be evaluated, without greatly impacting the final costs.

A further analysis was performed to evaluate the differential cost of installing V-RES plants in the North-Eastern part of the country, with respect to the optimal solutions identified in the previous stage that favours the V-RES localisation in the Western part of the country. The goal of this analysis is to support the identification of an optimal trade-off between installing V-RES plants in areas (West side) with high availability of V-RES but far from the load centres and requiring a massive investment in grid extension and reinforcement, with respect to installing plants in areas (North-East side) with higher LCOE but closer

to the load centres and therefore requiring less investments on grid reinforcement. The results indicate a differential cost over a horizon of 30 years of around 7.5 billion USD (Ⓢ 10.3 billion USD). Considering this value as a proxy for the cost-opportunity to invest in transmission grid expansion of the West-East corridor, it suggests that as long as the cost for reinforcing the infrastructure in the South-West area and the interconnection towards the load centres is significantly below this number, it may be worth to prioritize the Western areas with lowest LCOE for installing V-RES plants. This 7.5 (Ⓢ 10.3) billion-figure should be intended as the order of magnitude of the actual cost-opportunity to be further adopted in eventual strategic planning decisions. In fact, deeper cost-benefit and financial analyses, which are out of the scope of this study, should be taken into consideration in order to include also the factors that may have and incremental or decremental impact of that figure, such as the needs for grid reinforcements for the West-East corridor even in the "Nort-East reallocated" scenario.

Impact

A preliminary insight on the impact that new V-RES installations, considering a least-cost merit order logic, could have on the grid is provided. Four critical clusters are identified:

1. A 3.9 GW group in the north-west area of Northern Cape, composed by around 2.4 GW of solar PV and 1.5 GW of wind. In the whole Northern Cape, 0 GW of connection capacity is readily accessible as per GCCA, but relevant grid reinforcements are expected as per TDP 231.
2. A 5.1 GW group (mainly wind) on the line at the border between Northern Cape and Western Cape, and a 7.3 GW group (all wind) on the line at the border between Western Cape and Eastern Cape. According to the GCCA, the connection capacity readily accessible in the two Capes is not sufficient to host the new expected connections, but relevant grid reinforcements are expected as per TDP 231.
3. A 5.6 GW group (only solar) on the corridor in Free State. According to the GCCA, the connection capacity readily accessible in the Province is higher than 4 GW but is not sufficient to host the new expected connections. Again, relevant grid reinforcements are expected as per TDP 231.

In terms of impact on energy supply cost (and tariff, as a consequence), the commissioning of the new expected capacity may lead to a substantial decrease in the total weighted average supply costs from renewable IPPs for Eskom: from the 146.4 $/MWh of 2021 (based on the latest available data from the Eskom Integrated Report 2021) to around 50 $/MWh (Ⓢ 50 $/MWh) in 2031. In terms of total energy supply costs, the increment of the electricity demand, combined with an expected gradual increment of coal cost and with the assumption that renewables will displace coal generation (and eventually only to a minor extent OCGT and nuclear generation), would lead to a decrease in the total electricity supply costs in the country: from a pure energy balance perspective, others things being equal, V-RES at an upper limit of 50$/MWh (Ⓢ 50 $/MWh) may substitute alone 56 TWh of coal at 79 $/MWh (preventive estimation, which does not consider the frequent program of extraordinary maintenance on coal plants that reduce considerably the actual availability of these plants). This should bring about a reduction (or at least a stabilization) of the energy component of the electricity tariff.

Given the results and the outcomes of the presented works, some further steps could be suggested, to build upon the analysis with a concrete and fruitful approach.

- *Update the results with TDP2022.* The TDP2022 considers a longer horizon than the TDP2021, up to the year 2032. Also, it substantially increases the target quantities of V-RES from 2030 ongoing. Considering 2031, the expected target quantities for wind and solar envisaged in TDP2022 are 3.8 GW and 8.2 GW more than the ones considered in the TDP2021. Moreover, the new TDP2022 also considers a massive implementation of battery energy systems, whose impact on the optimal allocation and related LCOE of V-RES is worth to be investigated.

- *Extended V-RES integration.* Identify the optimal V-RES mix standing on the all the existing and planned substations that maximizes the contemporaneity between V-RES generation and load supply, by building upon the potential complementarity of PV, wind, storage, and load profiles during the days of the year.
- *Network Study to analyse the optimal interconnection option.* Evaluate which could be the optimal interconnection options of the new V-RES plants to the existing and planned grid, through an integrated step-by-step approach: 1) consideration of obstacles and preferable routes, 2) engineering considerations on S/S expansion, 3) network study to assess the feasible connection schemes, 4) grid routing to identify the optimal path for connection to the S/S. All these steps should be based on an identified roadmap (e.g., next 5 / 10 / 15 years).
- *Detailed Reliability and Adequacy study.* The activity consists of performing a detailed study, which would take into account all such additional costs and opportunities, and indicators of reliability and adequacy, that aims at defining a robust evaluation of the maximum V-RES capacity in the different sites and the whole system, and the related electricity supply cost. This can be implemented through hourly-based probabilistic demand-supply simulations performed considering also the actual grid topology.
- *Mini-grid implementation.* Consider some of the areas that are promising from the standpoint of resources availability but that are far or isolated from the existing grid, as possible locations for standalone microgrids deployment.

ANNEX A – RESUMING GEOSPATIAL FILES OUTPUTS

The output files, of raster and vector formats, are provided for both the base case and the sensitivity analysis.

Step 1: Geospatial Data Collection and Creation of Solar and Wind Atlases

1. *GHI Atlas*: one (1) raster file (.tiff format), with pixel size equal to around 250x250 m^2. Pixel values expressed in kWh/m^2/year.
2. *GTI Atlas*: one (1) raster file (.tiff format), with pixel size equal to around 250x250 m^2. Pixel values expressed in kWh/m^2/year.
3. *Wind Speed Atlas*: three (3) raster files (.tiff format), with pixel size equal to around 250x250 m^2. Pixel values expressed in m/s. Heights above ground: 50, 100, and 150m.
4. *Weibull A Atlas*: three (3) raster files (.tiff format), with pixel size equal to around 250x250 m^2. Pixel values expressed in m/s. Heights above ground: 50, 100 and 150m.
5. *Weibull k Atlas*: three (3) raster files (.tiff format), with pixel size equal to around 250x250 m^2. Pixel values are adimensional. Heights above ground: 50, 100 and 150m.
6. *Html map*: file composed of 4 interactive maps showing the value of GTI and wind speed@100m in the whole South Africa and in the Admissible areas.

Step 2: Identification of Resources Technical Potential (Capacity Factor Assessment)

7. *Solar Production Atlas*: one (1) raster file (.tiff) for energy yield and one (1) raster file (.tiff) for CF with 1 x 1 km^2 resolution.
8. *Wind Production Atlas*: four (4) raster files (.tiff) with energy yield @90m, 100, 120m and 140m and four (4) raster files (.tiff) with CF @90m, 100 ,120m and 140m.
9. *Html map*: file composed of 4 interactive maps showing the value of Energy Yield and CF od PF and Wind @100m.

Step 3: Analysis of V-RES Availability

N/A

Step 4: Calculation of V-RES KPIs

10. *Solar LCOE-Capacity-Energy Atlas*: one (1) vector file (.shp format) composed by Elementary Units with associated the average *KPI-LCOE* [$/MWh] (attribute "LCOE"), the associated potential *KPI-Maximum Installable Capacity* [MW] (attribute "P [MW]"), and the expected *KPI-Yearly energy production* [MWh/year] (attribute "E [MWh]") of solar PV.
11. *Wind LCOE-Capacity-Yield Atlas*: seven (7) vector files (.shp format) composed by Elementary Units with associated the average *KPI-LCOE* [$/MWh] (attribute "LCOE"), the associated potential *KPI-Maximum Installable Capacity* [MW] (attribute "P [MW]"), the expected *KPI-Yearly energy production* [MWh/year] (attribute "E [MWh]") of wind, and the IEC class at the four different hub heights and for the "Small" and "Big" reference turbines.

Step 5: Optimization of V-RES Integration

12. *Integrated V-RES Atlas*: three (3) vector files (.shp format), one for each optimization method described above, where solar and wind allocation have been optimized in each Elementary Unit based on the optimization logics described above. The files will report the *KPI-LCOE* [$/MWh]

(attribute “LCOE”), the associated potential *KPI-Maximum Installable Capacity* [MW] (attribute “P [MW]”), and the expected *KPI-Yearly energy production* [MWh/year] (attribute “E [MWh]”) of the optimal resource in each Elementary Unit.

Step 6: Power System Implications

13. *Selected Areas Atlas*: six (6) vector files (.shp format) with the Elementary Units selected in each scenario (Scenario 1, Scenario2 and Scenario 1-Stage2) for wind and PV resources, with associated the installed power (attribute “P [MW]”), the energy produced (attribute “E [MWh]”) and the LCOE (attribute “LCOE-$/MWh”)) and the total Admissible Area (attribute “Area [m^2]”).
14. *Centroid Atlas*: six (6) vector files (.shp format) with the centroids of power of wind and PV installations, with associated the capacity P[MW].

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