Integration of Non-Programmable Renewable Energy

in the National Electric System of South Africa

Phase 2



RES4AFRICA FOUNDATION

Integration of Non-Programmable Renewable Energy in the National Electric System of South Africa

Optimal VRE & BESS assessment study

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.
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About the Southern Africa Programme

RES4Africa's Southern Africa 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 southern 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.

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ABBREVIATIONS

BESIPPPP	Battery Energy Storage Independent Power Producers Procurement Programme
BESS	Battery Energy Storage System
BQ	Budget Quote
CF	Capacity Factor
CoCT	City of Cape Town
CSP	Concentrated Solar Power
DC	Duration Curve
EC	Eastern Cape
FS	Free State
GCCA	Generation Connection Capacity Assessment
GT	Gauteng
HC	Hydra Cluster
IPP	Independent Power Producer
IRP	Integrated Resource Plan
KN	KwaZulu-Natal
LCOE	Levelized Cost of Electricity
LF	Load flow
LI	Limpopo
MILP	Mixed-Integer Linear Programming
MP	Mpumalanga
NC	Northern Cape
NW	North West
NTC	Net Transfer Capacity
RMIPPPP	Risk Mitigation Independent Power Producer Procurement Programme
S/S	Electrical Substation
TDP	Transmission Development Plan
V-RES	Variable Renewable Energy Sources (solar and wind)
WC	Western Cape

EXECUTIVE SUMMARY

In the framework of the previous activity committed by RES4Africa to CESI, namely the *study Integration of Non-Programmable Renewable Energy in the National Electric System of South Africa*[1], a geospatial analysis was performed, aimed at exploring the value of V-RES (i.e., solar and wind) in South Africa. Following that, Eskom and RES4Africa identified the need to test an alternative methodology, based on PLEXOS energy modelling tool, to identify the maximum connection capacity of V-RES and BESS that can be integrated into the South African supply areas (cf. GCCA terminology), which would allow to build upon the potential complementarity of PV, wind, storage, and load profiles during the days of the year, as well as the curtailment practice.

To achieve this goal, we implemented a methodology that envisaged[2]:

1. The modelling of each supply area separately (referred to as Standalone Supply Areas models), that adopted the GCCA 2024 data.
2. The modelling of the interconnected region (referred to as Interconnected model) of WC, EC, NC, HC, FS and NW based on GCCA 2025 data.

The main outcomes and insights from the analysis are highlighted in grey boxes.

Step 1: Supply areas models (according to GCCA 2024)

The goal of the first step of the study is modelling the areas of Western Cape, Eastern Cape, Northern Cape, and Hydra Cluster as separate regions. Various scenarios, on BESS and admissible curtailment, are explored to assess the balance between supply and demand in these regions, in order to:

i. Assess the maximum theoretical potential of V-RES installation in the supply areas.
ii. Test the potential overall system benefits of a systematic curtailment practice.
iii. Evaluate the areas where BESS may bring the largest benefit to the system.

For the *Standalone Supply Area* model: 5 Scenarios have been simulated for Western Cape, Eastern Cape, Northern Cape, and Hydra Cluster:

1. No curtailment – No BESS.
2. No curtailment – 2 GWh/0.5 GW BESS
3. 10% Annual Curtailment – No BESS
4. 10% Annual Curtailment – 2 GWh/0.5 GW BESS
5. 10% Annual Curtailment – 3.2 GWh/0.8 GW BESS

Data and information have been derived from GCCA 2024 and ESKOM datasets and added in PLEXOS as input parameters.

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[1] *See the V-RES Localisation Study here: https://res4africa.org/wp-content/uploads/2023/03/integration_SA_v1-combined-1.pdf*
[2] *It is noted that the study was developed in concomitance with the drafting and release of the GCCA 2025 by Eskom. Therefore, the report follows this temporal work flow by relying on the latest GCCA reports that were available at the time the activities were performed.*

Nota bene: on the BESS scenarios, it is important to highlight that the limited amount of capacity tested in the parametric analysis is to be intended in light of the target year of the simulations (i.e., 2025). Testing larger sizes is not considered a realistic scenario that could be potentially feasible in 2025. At the same time, the results and conclusions on the BESS analysis must not be used to infer on the BESS advantages/ disadvantages in the long run, which is out of the scope of the analysis.

Outcomes (1/2) – Step 1

The following considerations can be derived:

- **Western Cape** has good wind resource availability, which encourages wind over PV installations. The biggest system benefits, in terms of installing additional capacity and maximizing exports as a result, come from scenarios with 10% curtailment. BESS alone do not have a significant impact on the new installable V-RES capacity, but it allows to significantly increase the exported energy. In the case without curtailment, it is in fact used for peak shaving purposes, especially in the periods with high wind availability and low load demand, allowing to increase the installed wind capacity. When combined with curtailment, BESS have an effect on the new PV capacity installable in the region, with however minor impact on the exports. Finally, the province would become a significant net exporter when the dispatching on the region is appropriately optimized.
- In **Eastern Cape**, the 10% curtailment practice does offer the biggest system benefits in terms of increased installation capacity and export maximization. BESS, on the contrary, have a low added value.
- In **Northern Cape** the results show that the current network congestions in the region do not allow to install additional wind and PV capacity, in the absence of curtailment or BESS. Curtailment is more advantageous for increasing wind capacity rather than PV, because PV plants are congesting the system, with an almost flat profile, during the middle hours of the day. In the wind + PV scenario, BESS allow the installation of new wind capacity and the peak shaving on existing PV. On the other hand, in the PV only scenario, adding BESS is essential to increase PV capacity, despite at a lower extent than what is achievable with curtailment.
- In **Hydra Cluster**, BESS combined with curtailment have a significant positive impact especially on new PV installations. Still, curtailment alone provides the largest marginal benefits to both V-RESs. The solution involving the hydro plants' optimized dispatching allows for a greater penetration of V-RES, given the increased flexibility in the system. It is noted also that the additional capacity resulted from PLEXOS exceeds the current expected maximum available capacity of the total S/Ss in Hydra Cluster (=1.3 GW, net of the planned *"new" Hydra D, Hydra B, and Gamma*).

	ADDITIONAL RES capacity (MW) & EXPORT (GWh)																	
	SCENARIO 1			SCENARIO 2			SCENARIO 3			SCENARIO 4			SCENARIO 5			STOCHASTIC		
	No BESS + No curt			BESS 2GWh+ No curt			No BESS + curt10%			BESS 2GWh+curt10%			BESS 3.2GWh+curt10%			BESS 2GWh + curt10%		
	PV	Wind	Export	PV	Wind	Export	PV	Wind	Export	PV	Wind	Export	PV	Wind	Export	PV	Wind	Export
EC		1488	10048		1870	11377		3798	16276		4004	16903		4106	17233			
WC	353	2173	17697	172	2873	20269	2270	4892	28674	4057	4367	29854	4289	4372	30227			
$HC_{hyd\ prof}$	0	1152	10387	0	1515	12019	170	2935	17020	1845	2535	18920	2046	2549	19358			
$HC_{hyd\ opt}$	0	1712	13073	0	2075	14700	1724	2601	19192	2046	2692	20161	2251	2710	20624			
NC	0	78	5942	0	584	7277	0	3286	15726	0	3608	16623	0	3750	17031	0	3531	16011
$NC_{only\ PV}$	71		5895	577		6580	1988		9223	2452		9666	2721		10008	2383	0	9379

Step 1 also includes the BESS analysis. It consists of the valorisation of the V-RES energy accumulated by the BESS that otherwise would be lost. It is calculated as the additional export and local load supply achievable with the BESS, with respect to the no-BESS case.

Outcomes (2/2) – Step 1

From a pure energy-perspective, the results do not highlight one area as much more appropriate than the others for the installation of BESS. In fact:

1. Without the 10%-curtailment practice:
a. Northern Cape is the area where BESS is utilized the most (almost at least twice as much as Western Cape and Eastern Cape) and it is the region that benefits from a higher relative increment of new V-RES, with respect to other areas.
b. In all the areas, the introduction of BESS allows to achieve system balancing benefits (i.e., to increase the exports towards neighbouring areas and to satisfy the internal load) that off-set the cost of BESS itself. The ratio between V-RES value / BESS cost is in favour of Western Cape, followed by Northern Cape, Hydra Cluster, and finally Eastern Cape.
c. In all the supply areas, the gains in terms of additional absolute V-RES are almost similar.

2. With the 10%-curtailment practice:
a. Western Cape and Hydra Cluster benefits from a higher absolute increment of new V-RES, with respect to other areas.
b. Northern Cape benefits from a higher relative increment of new V-RES, with respect to other areas.
c. Western Cape is the area where BESS is utilized the most, immediately followed by Northern Cape.
d. The ratio between V-RES value / BESS cost is in favour of Hydra Cluster, followed by Western Cape, Northern Cape, and finally Eastern Cape.
e. In all the areas, the benefits achievable from the 10%-curtailment (additional V-RES and export) offset the potential benefits achievable from BESS.

Given the above, these are the conclusions in terms of BESS analysis:

1. The areas with no carrying capacity available and the areas with system balancing and ROCOF issues should be prioritized for BESS installations.
2. Where there are less balancing/inertia problems and available supply area capacity, the curtailment outperforms the BESS advantages in terms of increasing V-RES penetration. This consideration shall be understood in the context of the Nota bene above regarding the interpretation of BESS size scenarios at the light of the reference horizon (2025).

Table below reports the results in terms of relative and absolute increment of new V-RES of the various scenarios with respect to the No BESS + No curt case.

	BESS 2GWh+No curt		No BESS+curt10%		BESS 2GWh+curt10%		BESS3.2GWh+curt10%	
Add. V-RES	**%**	**MW**	**%**	**MW**	**%**	**MW**	**%**	**MW**
EC	+26%	+382	+155%	+2310	+169%	+2516	+176%	+2618
WC	+21%	+519	+184%	+4636	+233%	+5898	+243%	+6135
NC	+649%	+506	+4113%	+3208	+4626%	+3530	+4708%	+3672
$NC_{only\ PV}$	+713%	+506	+2700%	+1917	+3454%	+2381	+3732%	+2650
$HC_{hydro\ profiles}$	+32%	+363	+170%	+1953	+280%	+3026	+299%	+3443
$HC_{hydro\ opt}$	+21%	+363	+153%	+2613	+177%	+3208	+190%	+3249

Step 2: Interconnected model (based on GCCA 2025)

This second step consists of modelling the areas of Free State and North West as separate regions, and in re-simulating the Western Cape, Eastern Cape, Northern Cape, Hydra Cluster, Free State and North West as a single interconnected region (hereinafter referred to as Interconnected model) based on GCCA 2025 data. These include the fine-tuned additional PV and wind capacity, new BESS capacity, and interconnections topology and limits. Two (2) additional BESS scenarios are implemented: one with 2GWh/0.5 GW BESS in Northern Cape only (Base case), and one with 2.46 GWh/0.615 GW BESS in both Free State and North West. The objective is to:

i. Define the new additional PV and wind capacity that can be potentially installed in each supply area, considering them an interconnected system.
ii. Simulate the new optimal intra-area dispatching.
iii. Derive the maximum hourly export profile from the WC+EC+NC+HC+FS+NW region and dividing them between MP, KN, GT and LI.
iv. Identify the most congested areas (internal network) and interface corridors.

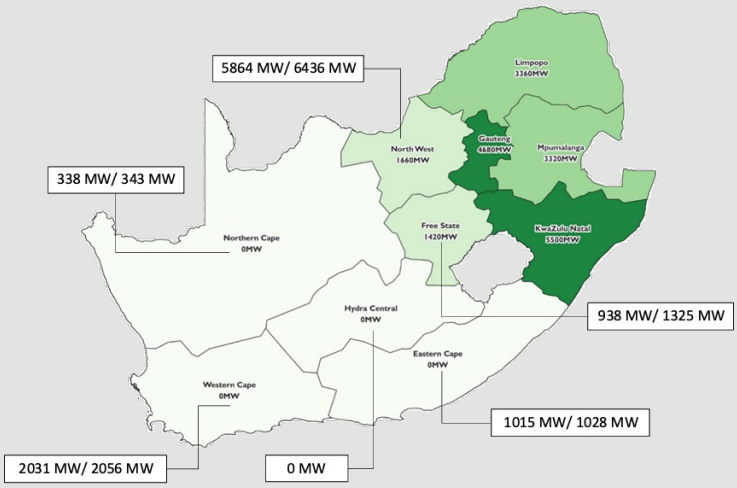
The following outcomes are obtained:

Outcomes (1/3) – Step 2

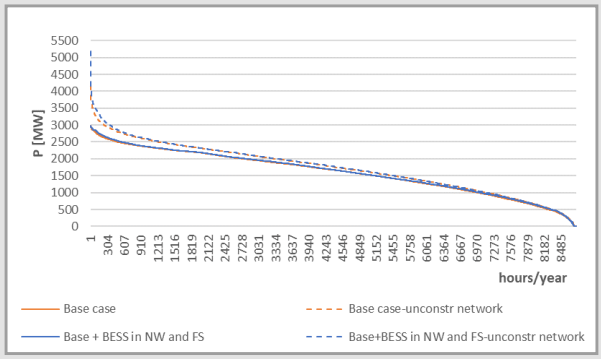
- In **Western Cape**, it is feasible to install 2031 MW of wind in the Base case, that slightly increases up to 2056 MW with BESS in NW and FS. PV power is not expected to be installed in the region. The corridor linked to Hydra Cluster is primarily used for exporting surplus generation that exceeds the local demand.
- Also in **Eastern Cape**, V-RES installations are characterized only by wind power: 1011 MW for the base case and 1028 MW for the case with BESS in NW and FS. This additional capacity results to be largely limited by the low NTC of the region, which considerably constraints the export from the area, and therefore the installable wind capacity.
- In **Northern Cape**, the additional V-RES capacity remains minimal, due to the limited hosting capacity of the Northern Cape network.
- No additional V-RES capacity is optimized in **Hydra Cluster**, reflecting its status as a transit area, which presents critical internal congestions that are preventing endogenous new V-RES capacity and limiting the evacuation of power from the Capes.
- In **Free State** and **North West**, only PV is expected to be integrated. The incorporation of BESS in these regions facilitates a substantial increment in the potential for PV installations for the internal supply-demand balance, which plays a pivotal role for the reduction of the endogenous coal plant usage in Free State and the import of power (mainly thermal-based) in North West.
- For what concerns the external areas, **Mpumalanga** is connected to Free State and Hydra Cluster, and its maximum supply capacity (3320 MW) is saturated almost all the hours of the year, acting as the main "outlet" of the V-RES production from the inner regions. This suggests the following interesting output: the capacity freed-up by the expected decommissioning of coal power plants in MP would serve to increase the production and evacuation of more V-RES import, especially the PV production during the day. This reduces the room and interest for a direct replacement of the coal plants with local PV installations in MP, while wind may be a more interesting option to investigate. **KwaZulu Natal** is connected only to Eastern Cape, and its import is largely constrained by the NTC of this region. The export towards **Gauteng and Limpopo** is limited by the NTC of North West, which

reflects the fact that the corridor is only used to evacuate the extra PV generation from North West, since the import from Northern Cape is only used to satisfy the internal North West load.

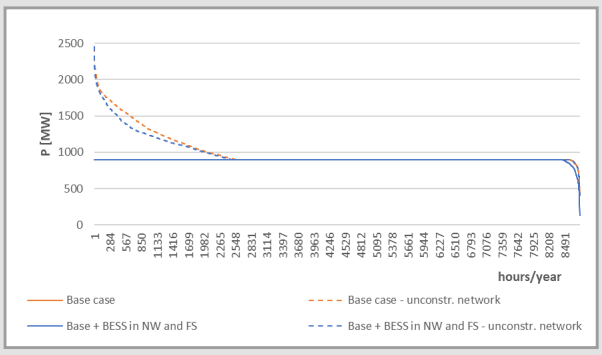
The figure below resumes the main results obtained in terms of additional total V-RES capacity (wind+PV) for both the scenarios (Base case/Base case + BESS in NW+FS), with respect to the GCCA figures. The Duration Curves (DCs) are also reported below, and clearly show that curtailment allows to unlock a considerably increase of V-RES production that would otherwise be possible only through a massive deployment of uneconomical grid investments (i.e., without curtailment, the grid should be reinforced up to a capacity able to accommodate the peak of the dotted lines, making it uneconomical since the benefits would be limited to few hours of the year).



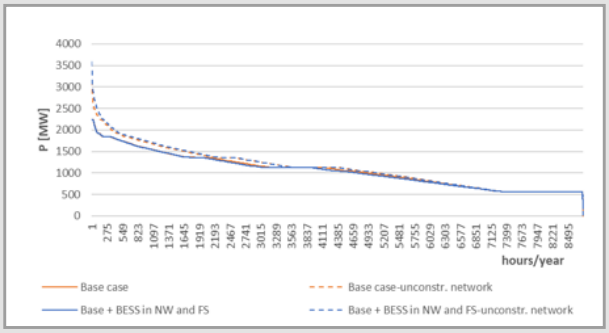
The figures below show the Duration Curves of the exports from the modelled supply areas.



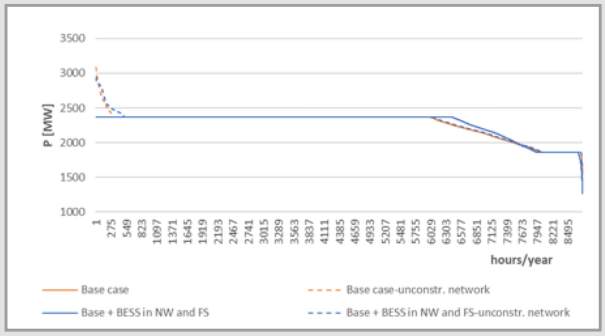
Western Cape



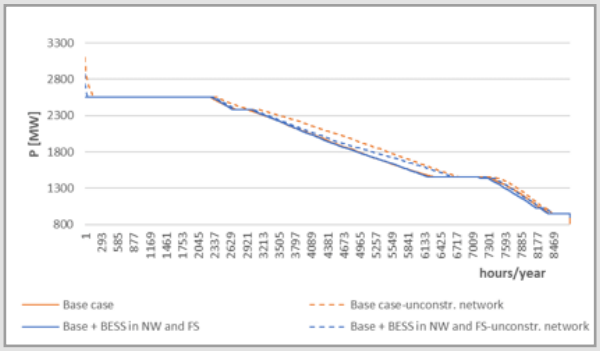
Eastern Cape



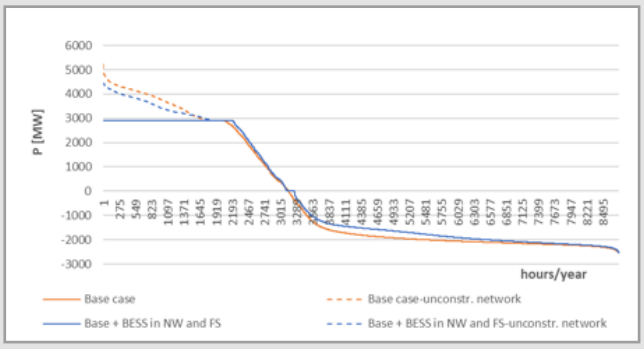
Northen Cape



Hydra Cluster



Free State



North West

Additional simulations are performed for both the scenarios with and without BESS in NW and FS, to test how the result would change without the 10%-curtailment practice, and by applying it exclusively to wind. The latter is tested alone in order to be conservative towards the uncertainties on the nature of future PV penetration (i.e., utility-scale vs rooftop, the latter being "uncurtailable").

Outcomes (2/3) – Step 2

- Curtailment significantly favours the integration of new wind capacity, unlocking new capacity that would be null in case of no curtailment. The impact on new PV is less pronounced (+24%-33% depending on the scenario).
- The total wind production increases by more than 50% with the curtailment practice, while the increase of PV production is almost negligible. Globally, the increase in the overall V-RES energy production allowed by the 10%-curtailment practice is around +23-25% depending on the scenario, offsetting considerably the dumped energy due to curtailment.
- The 10%-curtailment applied to wind only would cause a slight decrease of the systems benefits, that is a reduction of the exported energy of around 2600 GWh.
- The implementation of the curtailment practice shall consider all the obligations that ESKOM has in terms of guaranteeing the minimum levels of network availability and the contractual arrangements with the existing IPPs. Attention should be paid to avoid discrimination between IPPs that are operating under different contract frameworks and conditions imposed by curtailment (e.g., operating IPPs vs IPPs in construction with already-signed PPA vs future RMIPPPP).
- In general, our results show that the expected benefits achievable from the massive increase of low-cost V-RES production that can be reached by curtailment (around 20% estimated above) can be the driver to remunerate back the deemed-but-not-evacuated energy (e.g., for existing IPPs) and/ or to cover the expected increase of the off-take tariff to compensate the possible losses of earnings (e.g., for new IPPs).
- With respect to a carpet-curtailment to all the V-RES fleet (existing and new), it should be considered the possibility to implement a punctual 10%-curtailment to address only the most critical plants in the most critical areas and situations, that, when curtailed in some circumstances, may bring the highest overall system benefits.

		Base case			Base case + BESS in NW and FS		
		w/ 10% curtailment	w/o curtailment	Δ%	w/ 10% curtailment	w/o curtailment	Δ%
TOT Production [GWh]	PV	28051	26906	**4.3%**	30329	29866	**1.6%**
	wind	31846	21087	**51.0%**	32063	20912	**53.3%**
	TOT	59897	47993	**24.8%**	62392	50778	**22.9%**

		Base case			Base case + BESS in NW and FS		
		w/ 10% curtailment only wind	w/o curtailment	Δ%	w/ 10% curtailment only wind	w/o curtailment	Δ%
TOT Production [GWh]	PV	26250	26906	**-2.4%**	28754	29866	**-3.7%**
	wind	31046	21087	**47.2%**	31070	20912	**48.6%**
	TOT	57296	47993	**19.4%**	59824	50778	**17.8%**

The final assessment entails the analysis of the intra-areas' congestions and the saturations on the main electric corridors during the V-RES curtailment periods, to inform possible network reinforcement strategies.

Outcomes (3/3) – Step 2

By analysing data from all the interconnection lines, considering the NTC, and curtailment hours for the different regions, critical issues become apparent. Notably, the connection between Northern Cape and Free State emerges as a highly constraining interface. Simultaneously, the NTC of Eastern Cape and Hydra Cluster pose a significant barrier to achieving higher V-RES installations in the Capes. Also, the interfaces between Western Cape-Northern Cape and the Northern Cape-North West are saturated for most of the year, indicating that releasing such constraints would benefit the possibility to evacuate power through the entire upper corridor from Western Cape to North West. Finally, although less conspicuous, congestions exist on the lines between Free State and Mpumalanga, as well as on the NTC of North West.

It shall be noted that, being this analysis a purely energy optimisation, it does not reflect the actual "impedance map" of the grid that might give different results. Therefore, these conclusions shall be read as possible indications that hint at corridors/areas that may be worth to be investigated in consequent network studies.

The following table summarizes the levels of saturations on all the interconnections and NTCs, which are utilised more than 90% of their maximum limit for at least 60% of the curtailment hours in the corresponding supply area. The column "Hours of saturation" reports the total number of hours during which the Interconnection/NTC is utilized above 90% of its limit, and, in bracket, the subset of hours when also curtailment in one or more supply areas is experienced.

	WC	NC	EC	HC	NW	FS	Hours of saturation (of which hours of curtailment)
WC-HC							0
WC-NC	X		X	X			6939 (3614)
HC-NC							1601 (1029)
NC-FS	X	X	X	X	X	X	4357 (3076)
NC-NW	X		X	X			6717 (2980)
EC-FS							1355 (450)
EC-KN							0
HC-EC							0
HC-FS							0
HC-MP							1943 (1553)
FS-MP		X			X	X	5867 (2600)
NW-(GT+LI)							0
WC-NTC							24
NC-NTC							73 (29)
EC-NTC	X	X	X	X	X	X	8707 (4880)
HC-NTC	X	X	X	X	X	X	6994 (4026)
FS-NTC							0
NW-NTC		X			X	X	2231 (2030)

OVERALL CONCLUSIONS

In conclusion, the study allows to highlight the following key-messages:

1. The adopted approach confirms that building upon the possible complementarity of the PV and wind and the contemporaneity of V-RES output with load demand, a proper integration of BESS, and a prudent application of curtailment would allow to unlock a significant additional amount of new V-RES, that would be otherwise prevented in almost all the western supply areas.
2. In terms of dispatching and operation, the point above translates into the need to possibly revise the dispatching processes of ESKOM to properly manage the challenges imposed by a system that is becoming increasingly decarbonized. For example: with new V-RES penetration, the time period where the grid usage is maximised is likely to be during the daily hours (when PV is on), and this will require to consider revising the operational planning practices to maximise maintenance during the night hours. Similarly, also pumped-hydro-storages and hydro plants dispatching profiles should be re-optimized to better accommodate and maximize V-RES production.
3. Curtailment practice brings substantial system benefits, that, up to a certain extent, would be otherwise reachable only through uneconomical grid investments. All the stakeholders involved in the various sectors of the full electricity-supply chain would benefit from a carefully regulated and optimized application of curtailment: the IPPs-sector would gain from the increased available supply area capacity "unlocked" by curtailment; ESKOM, as system operator, would increase the available resources to dispatch the system, solve congestion, and balance the system; consumers would benefit from an expected increase in the security-of-supply (reduced load shedding), a more decarbonized system and possible reduction in the cost of electricity.
4. Our results show that the expected benefits achievable from the massive increase of low-cost V-RES production that can be reached by curtailment (around +20%) can be the driver to remunerate back the deemed-but-not-evacuated energy (e.g., for existing IPPs) and/or to coverage the expected increase of the off-take tariff to compensate the possible losses of earnings (e.g., for new IPPs). However, any implementation scheme of the curtailment practice shall be properly regulated and shall consider all the obligations that ESKOM has in terms of guaranteeing the minimum levels of network availability and the contractual arrangements with the existing IPPs. Carefulness and attention should be paid to avoid discrimination between IPPs that are operating under different contract frameworks and conditions imposed by curtailment (e.g., operating IPPs vs IPPs in constructions with already-signed PPA vs future RMIPPPP).
5. The results in terms of PV capacity that could possibly be integrated in the system do not discriminate between utility scale and smaller residential rooftop/commercial PV installations. Therefore, future rooftop PV penetration should be carefully addressed and wisely investigated, since it has an impact both on the possibility to integrate additional utility scale plants and on the expected benefits of the curtailment practice.
6. The results reveal that curtailment and BESS alone do not off-set the limitations imposed by the existing congested network topology, which remain an important limiting factor to a further increment of V-RES, needed to couple the gradual and expected decommissioning of thermal power plants in the easter side of the country. This still calls for strategic investments in reinforcing both the internal network components and some strategic inter-areas corridors.
7. Given the complexity of power systems, the results achieved with this energy-based study require further iterations with additional network studies to validate the results also from a power system perspective.

1 - INTRODUCTION

1.1 - Background

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. Remarkably, the latest Transmission Development Plan (TDP) 2023-2032 of Eskom substantially increased these targets, considering around 53 GW of V-RES installed by 2035 and 8.5 GW of batteries. 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. In the framework of the previous activity committed by RES4Africa to CESI, namely the study *Integration of Non-Programmable Renewable Energy in the National Electric System of South Africa* – hereinafter referred to it as "V-RES Localisation study" – a geospatial analysis was performed, aimed at exploring the value of V-RES (i.e., solar and wind) in South Africa, concerning the following aspects:

- *Potential*: expected specific Yield [kWh/kWp] of V-RES with high spatial resolution.
- *Exploitability*: proposal of candidate V-RES generation 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.

Based on the results of the study, Eskom and RES4Africa identified the following two forthcoming needs worth of being further evaluated through a deepest analysis:

1. The "V-RES Localisation study" analysed wind and PV from the energy, capacity, and cost perspectives separately, without leveraging on the benefits from their integration. Only a numerical case-study was performed for the Komsberg S/S upon request of RES4Africa. Eskom is deeply interested into extending the analysis of the benefits achievable from wind and PV integration on the whole South African system, disaggregated by *supply areas* (cf. GCCA terminology), in order to better inform the next annual GCCA Reports in terms of maximum capacity that can be installed.
2. The "V-RES Localisation study" did not consider the Battery Energy Storage Systems (BESS), since it was performed based on the TDP 2022-2031 (the latest available at the time the study was performed) which did not consider a significant deployment of BESS. Eskom is interested into quantifying the benefits of batteries to foster a deeper V-RES integration and contribute releasing the current issue of capacity constraint that the South African electricity system is experiencing.

1.2 - Rationale

The two above-mentioned additional needs stand on the fact that the topology of the South African grid is expected to dramatically change. In fact, so far, the South African system has been characterized by the following well-known peculiarities:

1. *South-West side of the system*: minority of national load, abundance of V-RES resource, weaker grid, little synchronous capacity installed.
2. *North-East side of the system*: majority of national load, little V-RES resource, stronger grid, majority of synchronous capacity installed.

With the expected increase of penetration of V-RES (i.e., PV and wind) into the South-West side of the South African system and the gradual decommissioning of the conventional coal-based thermal power plants in the East side, the net power exchanged within the internal networks of the *supply areas* and the net transfer from the West side towards the East side is expected to substantially increase. This calls for urgent investments to reinforce both the internal network elements in the West side of the system and the transmission corridors that connect the West side to the East side, since this impacts in turn on the capability to accommodate and evacuate new V-RES capacity from the West, where the grid is currently more congested and weaker.

Looking forward to these medium- to long-term investments, every year Eskom provides short-term signals to the stakeholders (e.g., developers, IPPs) who seek to invest in V-RES plant to connected onto Eskom grid. This is provided yearly through the Generation Connection Capacity Assessment (GCCA) report, which aims at giving stakeholders an indication of the available capacity for the connection of new generation at the main transmission system substations on the Eskom transmission network. Since the GCCA has a short-term forward-looking horizon, it forecasts the calculation of the available capacity based on the reinforcements on the grid that are expected to be available in the next immediate future.

In this context, an appropriate short-term instrument to maximize the penetration of V-RES, which is complementary to the reinforcement of the grid, is the optimization of the dispatching practices. These should build upon the possible complementarity of the PV and wind and the contemporaneity of V-RES output with load demand – the latter by relying both on the "natural" coincidence (e.g., PV output during daily peak hours or wind blowing mainly during the night hours) or on a "forced" one (through peak-load shifting with BESS).

1.3 - Objective of the study

Based on the previous considerations, the goal of this study is to identify the maximum connection capacity of V-RES and BESS that can be integrated into the South African *supply areas* (cf. GCCA terminology), 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.

More specifically the following aspects will be investigated:

1. Demand-supply reference energy system modelling for the relevant (viz. more critical) South African *supply areas* – i.e., modelling of the generation (existing and future V-RES), storage, load profile, and the feasible *supply areas* exchange.
2. Simulation of the hourly dispatching, prioritizing the V-RES generation to supply local load and maximising the inter-areas power transfers.
3. Final Quantification of the maximum V-RES & BESS mix by *supply areas*, in order to 1) maximise the penetration of V-RES, 2) maximise the export from the West to the East side of the country. without violating the inter-areas transfer capacity.

The scope of work does not include:

1. The assessment of the inter-areas transfer capacity (that is, the NTC) of each *supply area*. This is considered an input from ESKOM.
2. Any power system study on the South African grid.
3. Reliability and adequacy analysis.

1.4 - Scope of the Report

The present report is the Final Report that covers all the activities performed in the study.

The study was developed in concomitance with the drafting and release of the GCCA 2025 by Eskom. Therefore, the report follows a temporal workflow by relying on the latest GCCA reports that were available at the time the activities were performed. More specifically, the study is divided into two main parts, developed sequentially:

1. Standalone Supply Areas analysis: the areas of Western Cape (WC), Eastern Cape (EC), Northern Cape (NC), and Hydra Cluster (HC) are modelled and simulated as separate regions, on the basis of GCCA 2024. The goal is to maximise the V-RES penetration and the export of each area individually.
2. Interconnected model analysis: the South-West side of South Africa is modelled and simulated as a single interconnected system composed of the supply areas of Western Cape (WC), Eastern Cape (EC), Northern Cape (NC), Hydra Cluster (HC), Free State (FS), and North West (NW) on the basis of GCCA 2025. The goal is to maximise the V-RES penetration in the system and the export towards the East side of the country.

2 - MATERIAL AND METHODS

2.1 - Methodology

In accordance with Eskom and RES4Africa, the whole study focuses on the *supply areas* where the grid is most congested, constraining the penetration of V-RES in South Africa, namely:

1. Western Cape (WC).
2. Eastern Cape (EC).
3. Northern Cape (NC).
4. Hydra Cluster (HC).
5. Free-State (FS).
6. North West (NW).

In the remaining supply areas, no grid congestions are expected to significantly limit the connection capacity of generations. Therefore, they are modelled as "sinks" limited by their supply area capacity. The present report examines the full study, explaining the sequential steps undertaken to formulate it.

The study is performed in accordance with the following steps:

1. **STEP 1**: Based on GCCA 2024, we modelled the areas of WC, EC, NC, and HC as separate regions (hereinafter referred to as *Standalone Supply Areas* models) following GCCA 2024 data. Various scenarios (on BESS and admissible curtailment, see section 2.2 for more details) are explored to assess the balance between supply and demand in these regions. For all the regions, the following are evaluated:
   (i). The additional PV and wind capacity that can be potentially installed in each supply area.
   (ii). The optimal intra-area dispatching.
   (iii). The maximum potential hourly export profile from each *supply area*.
   The aim of testing the *Standalone Supply Areas* models is:
   1. To assess the maximum theoretical potential of V-RES installation in the *supply areas*.
   2. To test the potential overall system benefits of a systematic curtailment practice.
   3. To evaluate the areas where BESS may bring the largest benefit to the system.

2. **STEP 2**: We introduced the transit areas of FS and NW, and we modelled the WC, EC, NC, HC, FS and NW as a single interconnected region (hereinafter referred to as *Interconnected* model), based on Eskom's feedback on the additional PV and wind capacity and BESS capacity calculated at previous step, and the interconnections topology and limits. The following are evaluated:
   (i). The new additional PV and wind capacity that can be potentially installed in each *supply area*.
   (ii). The new optimal intra-area dispatching.
   (iii). The maximum potential hourly export profile from the WC+EC+NC+HC+FS+NW region and their subdivision between Mpumalanga (MP), KwaZulu-Natal (KN), Gauteng (GT) and Limpopo (LI).
   The final outcomes of the *Interconnected* model are:
   1. The additional PV and wind capacity that can be potentially installed in WC, EC, NC, HC, FS, and NW, in order to maximize the export towards the rest of the country.
   2. The optimal intra-area dispatching.
   3. The maximum potential hourly export that can be evacuated into the remaining supply areas.
   4. The analysis of the congestions on the interface corridors and internal to the supply areas.
   5. The estimation of the potential benefits attributable to the curtailment practice.

2.2 - Modelling framework

2.2.1 - The tool: PLEXOS

PLEXOS is an energy optimization and simulation software that enables efficient planning and operation of energy systems. It integrates various aspects of the energy sector, such as power generation, transmission, and consumption, to provide comprehensive analysis and decision support. At its core, PLEXOS utilizes advanced mathematical algorithms and modelling techniques to simulate and optimize energy systems. It considers a range of factors, including fuel prices, generation capacity, transmission constraints, and demand patterns, to identify the most cost-effective and reliable energy generation and distribution strategies.

PLEXOS was adopted since the software offers several key functionalities, that are useful for this study:

1. It enables users to model and simulate energy systems at different scales, from individual power plants to regional or national grids. This allows for a holistic understanding of the system dynamics and the assessment of potential impacts of various scenarios or policy changes.
2. PLEXOS performs optimization analyses to identify optimal generation schedules, subject to potential different objective functions, such as minimizing costs or maximizing renewable energy utilization.
3. It offers a good trade-off between detailed representation of the system and computational effort.
4. PLEXOS is the software currently used by the Planning department in Eskom.

2.2.2 - Model structure

2.2.2.1 - Standalone Supply Areas

PLEXOS is used to model the supply areas under analysis with the objective to identify the optimal V-RES and BESS integration that maximizes the export potential by building upon the potential complementarity of PV, wind, storage, and load profiles during the days of the year. The objective of maximising exports, within the limits of the Net Transfer Capacity (NTC), is because in the supply areas analysed, the expected production will mainly be exported to the north-eastern part of the country. This, as explained above, is due to the peculiar nature of the South African system in which the load centres are concentrated in the East of the country, while the most attractive areas for production are in the West. The constraint on the NTC is intended to avoid non-evacuated generation from the western part of the grid (which is the weakest) to the eastern part (which has no significant congestion problems, as indicated by Eskom)

The model for each Standalone Supply Area is a regional model, meaning that only the inter-area network constraints are modelled, while the intra-area network of each supply area is modelled as a single node, being its modelling out of the scope of the study. A graphical representation of the boundaries of the model of each supply area is reported in Figure 2-1.

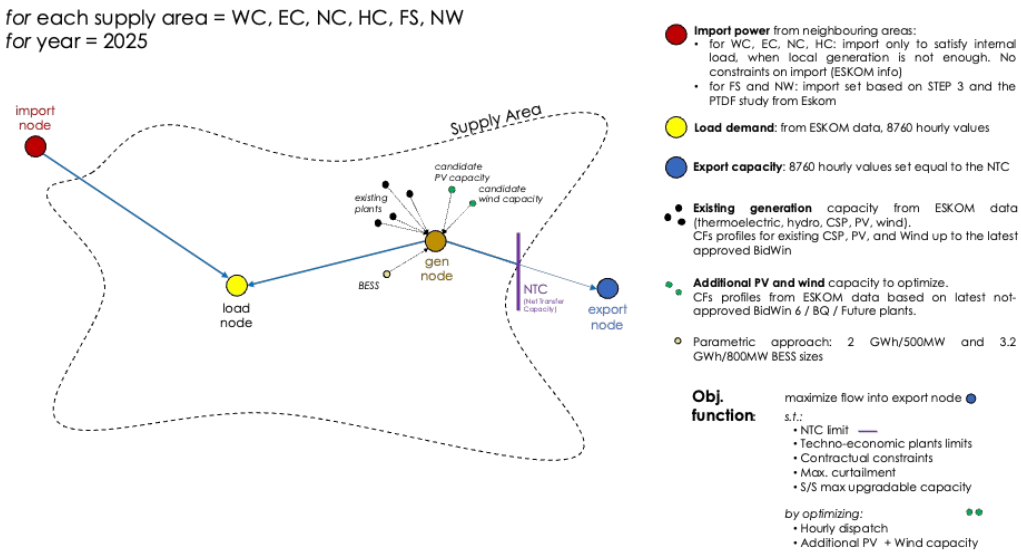


Figure 2-1. Standalone Supply Area PLEXOS's model structure at glance.

The demand-supply model for each supply area is based on a common Reference Energy System (RES, see Figure 2-2), which consists of four nodes:

1. The Generation Node, which includes all the generators and energy storage systems within the area.
2. The Load Node, representing the hourly energy demand of the area.
3. The Export Node, which accounts for the NTC and includes generators dedicated solely to meeting the export requirements.
4. The Import Node that calculates the amount of energy that needs to be imported from neighbouring areas:
    a. For WC, EC, NC, and HC the import is mainly to satisfy internal load, when local generation is not enough.
    b. For NW and FS, being them mainly transit area, the import represents the export from WC, EC, NC, and HC.

The facilities that are included in the model depend on the requirements and characteristics of the supply area itself and they belong to the following typologies:

- *Synchronous Generators*: each generator of the supply area is represented as a separated element. The generators have the possibility of providing energy to both the internal load and the export or, in some cases, they are only devoted to the export. Their dispatch is optimized based on the technical (see section 2.2.4) and operational constraints of each area (see section 2.3).
- *Existing V-RES*: All the renewable energy plants of the same typology (PV or wind) are grouped under a single equivalent power plant.
- *Additional V-RES*: This block models all the new V-RES capacity of the same typology as one single equivalent power plant. In this case the installed capacity is an output of the software optimization.
- *BESS*: This unit represents the Battery Energy Storage System (BESS) of the supply area, tested through a scenario-based parametric approach (see section 2.2.3).

In the Figure 2-2 a scheme of the Reference Energy model is represented.

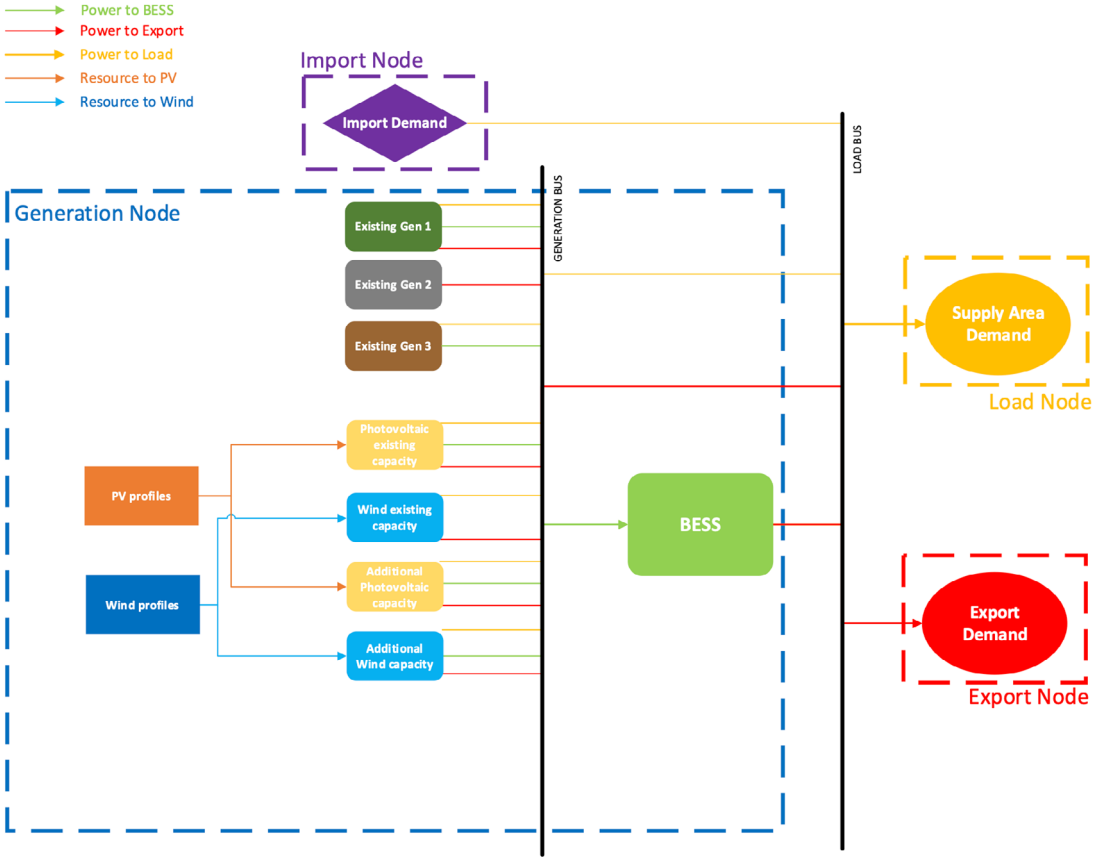


Figure 2-2. Reference Energy System. In the example, Existing Gen 2 can supply only the export node, and Existing Generator 3 cannot supply the export node.

2.2.2.2 - Interconnected Model

Following the individual assessments conducted for each specific area, the model, which initially comprises WC, NC, EC, and HC, is now interconnected by modelling the interconnecting corridors. Subsequently, the regions of FS and NW are incorporated, and these additional regions are included in the comprehensive evaluations of the results. The external regions of MP, KN, GT and LI are introduced only as equivalent load to enable the optimization of exports from the other regions.

More details on the *Interconnected* model are reported in section 2.5.

2.2.2.3 - Modelling hypotheses and settings

The following modelling settings and hypotheses apply to all the supply areas:

1. **Target Year**: 2025 to inform the next GCCA report.

2. **Dispatching strategy**: the optimization of the dispatch of energy generated by each power plant is optimized based on a given merit order set in the model, which prioritizes V-RES energy production, followed by nuclear plants, RMIPPPs units, other thermoelectric plants, and finally imported energy as the lowest priority. However, the optimization is subject to the constraint on minimum and maximum capacity factors (CF), which may result in prioritizing a generator with a lower merit order in some time-steps.
3. **Simulation time resolution**: hourly optimization, based on (forward-looking) weekly time steps.

4. **Export demand:**
   a. For the standalone supply areas models: the export demand from each *supply area* is modelled as a constant load equal to the NTC of the interested supply area, with the objective of maximizing the export.
   b. For the *interconnected* model: the export demand into MP, KN, LI, GT is modelled as a constant load equal to their respective supply capacity indicated in the GCCA 2025.

5. **Existing generation fleet**: provided by ESKOM in terms of:
   a. Installed capacity [MW]: This considers all the total thermal, hydro, and V-RES (up to the latest approved Bidding Window) generation fleet expected to be in operation by 2025.
   b. Hourly generation profile [MWh] for:
      i. Existing PV
      ii. Existing Wind
      iii. Existing CSP
      iv. Existing Hydro

6. **Existing Rooftop PV**: the GCCA 2025 included the presence of the installed rooftop PV in the *supply areas*, which impacts on a lower net load of the various areas. The installed capacity of rooftop PV in the various *supply areas* is received by ESKOM, while the profiles of expected generation was derived from open-access V-RES database[3]. Rooftop PV is implemented in the *Interconnected* model.

7. **Additional V-RES**: for each supply area, ESKOM provided the list of new solar and wind applications (not-approved BidWin6, BQ, "Future", see Figure 2-3) and the related 5-years generation profiles [MWh]. We calculated a single mean hourly generation profile yield [MWh/MW] for each application, and we finally *averaged*[4] such yield profiles of all the PV and Wind applications in same supply area to obtain a yield profile for a single equivalent candidate unit called "PV-new" and "Wind-new" for each supply area. The hypothesis is that the list of new solar and wind applications (not-approved BidWin6, BQ[5], "Future") received by Eskom is representative of the locations where it is more likely that future IPPs will go to invest in new V-RES capacity in the future capacity tenders.

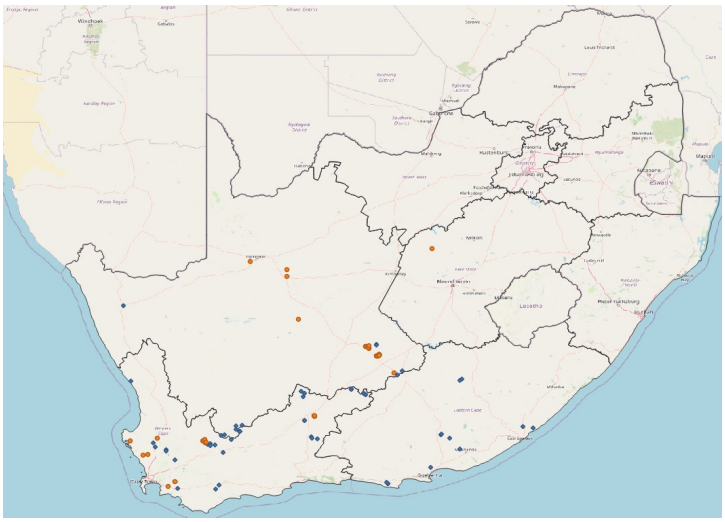


Figure 2-3. Localisation of the new solar and wind applications received from ESKOM with the related generation profiles.

[3] *SPV.GIS tool (https://re.jrc.ec.europa.eu/pvg_tools/en/, losses = 14%, optimal tilt and azimuth based on location).*
[4] *It shall be noted that the arithmetic average has been preferred over the weighted average, since it is more representative of the "location" of the applications, and independent from the candidate capacity of the received applications.*
[5] *For the standalone supply area simulations, the BQ have been considered as "new" since the GCCA 2024 reported almost zero allocated capacity for them. On the contrary, for the interconnected model simulations, the BQ have been considered as "existing", as per the GCCA 2025.*

8. **Gas-based units**: their dispatch is limited to a maximum annual Capacity Factor (CF) of 5%. This limitation is imposed due to the constrained gas supply in the country and has been mutually agreed upon with ESKOM. This condition does not apply to the Gas-based units belonging to the Risk Mitigation Independent Power Producer Procurement Programme (RMIPPPP).

9. **RMIPPPP plants**: The objective of the RMIPPPP is to address the existing short-term supply gap, alleviate electricity supply constraints, and reduce the extensive use of diesel-based peaking generators. The plants participating to this program are subject to specific criteria. These criteria include their availability between 5:00 and 21:30 and a minimum daily Capacity Factor (CF) of 50% within the time-window. These conditions have been incorporated into the simulation as imposed requirements.

10. **Curtailment**: The curtailment of renewable energy production is a significant topic. Allowing the curtailment of renewable energy production is crucial for several reasons in such contexts where the grid is not always able to evacuate the power generated by V-RES, as for the case of South Africa. During the discussions with ESKOM, it was agreed to set the annual curtailment limit at 10%, to investigate the global benefits in terms of additional capacity of V-RES that can be installed in the most congested areas. On this topic, it should be highlighted that this modelling decision reflects a purely system-wise technical consideration, and it does not assess the economic impact of the implementation of this choice at the level of the individual IPPs and on the off-take tariff, which should be considered case-by-case. For example, a certain level (%) of curtailment declared ex-ante by the grid operator may put an IPP in the position of applying a base rate proportionally increased to the % of declared curtailment, with the consequence that all the electricity produced would be purchased by the off taker paying the curtailments ex ante. Section 3.2.8 reports some significant quantitative considerations on the curtailment vs no curtailment situations.

11. **Cross-areas generators**: these are generators that belong to the electrical areas of 2 supply areas. These generators are therefore considered in the separated simulations of both the areas in the *Standalone supply areas* models. In the *Interconnected* model, they are placed in univocal areas.

12. **Substation (S/S) capacity**: for each S/S it has been identified:
    a. Load.
    b. Allocated V-RES capacity from Solar REIPPP, Wind REIPPP, RMIPPPP (and BQ[6]).
    c. Available capacity for new V-RES, based on the following formula:

$$1500\ MVA\ \times\ 0.95\ \frac{MW}{MVA} - \left(Solar_{REIPPP.cap}\ [MW] + Wind_{REIPPP.cap}\ [MW] + RMIPPP_{cap}\ [MW] - Load[MW]\right)$$

Where 1500 MVA is set because the current Eskom strategy to cope with the grid constraints within the supply areas is to proceed with reinforcing the internal grid in the areas where the V-RES plants are in the most advanced stages of their planning, requiring few years (2-3) for their completion. This timing is similar to the one necessary for Eskom to release the internal grid constraints, such as to extend a substation up to a total 1500 MVA transformers capacity. Also, only the S/Ss that have at least one 400/# kV transformer can be upgraded to 1500 MVA (otherwise the current transformer limit is considered) and only upon the transformers with the lower voltage side greater or equal than 132 kV.

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[6] For the standalone supply area simulations, the BQ have been considered as "new" since the GCCA 2024 reported almost zero allocated capacity for them. On the contrary, for the interconnected model simulations, the BQ have been considered as "existing", as per the GCCA 2025.

13. **Battery Energy Storage Systems (BESS)**: The evaluation of the introduction of BESS in the supply area is a crucial aspect. BESS plays a fundamental role in ensuring grid stability and flexibility, thereby facilitating the integration of renewable energy sources. Additionally, they contribute to managing peak loads, providing ancillary services, and optimizing energy cost. Therefore, a parametric study was conducted to evaluate the impact of BESS in each supply area, in accordance with the scenarios discussed at the following points. The selected power-to-energy ratio for BESS capacity is 0.25 (i.e., 4-hours BESS), as identified by ESKOM as appropriate for system balancing needs.

14. **Scenarios: based on the model configuration**:
    a. For the *Standalone Supply Area* model: 5 Scenarios have been simulated for WC, NC, EC, HC:
        i. No curtailment – No BESS.
        ii. No curtailment – 2 GWh/0.5 GW BESS
        iii. 10% Annual Curtailment – No BESS
        iv. 10% Annual Curtailment – 2 GWh/0.5 GW BESS
        v. 10% Annual Curtailment – 3.2 GWh/0.8 GW BESS

        The 2 GWh/0.5 GW is the 2023 tendered capacity in NC, and tested to assess, among other things, which would have been the benefit if a different area had been selected. The 3.2 GWh/0.8 GW is the forecasted capacity in 2025 in accordance with the latest TDP 2032, tested to assess the potential benefits in the extreme case as if the full TDP2025 BESS were all installed in the same supply area.
    b. For the *Interconnected* model: 6 Scenarios have been simulated for FS and NW (see more details in section 2.5):
        i. 10% Annual Curtailment – 2 GWh/0.5 GW BESS in NC
        ii. 10% Annual Curtailment – 2 GWh/0.5 GW BESS in NC- 2.46 GWh/0.615 GW BESS in FS and NW.
        iii. Without Annual Curtailment – 2 GWh/0.5 GW BESS in NC
        iv. Without Annual Curtailment – 2 GWh/0.5 GW BESS in NC- 2.46 GWh/0.615 GW BESS in FS and NW
        v. 10% Annual Curtailment only wind – 2 GWh/0.5 GW BESS in NC
        vi. 10% Annual Curtailment only wind – 2 GWh/0.5 GW BESS in NC- 2.46 GWh/0.615 GW BESS in FS and NW

        On the BESS scenarios, it is important to highlight that the limited amount of capacity tested in the parametric analysis is to be intended in the context of the target year of the simulations (i.e., 2025). Testing larger sizes is not considered a realistic scenario that could be potentially feasible in 2025. At the same time, the results and conclusions on the BESS analysis must not be used to infer on the BESS advantages/disadvantages in the long run, which is out of the scope of the analysis.

15. **Simulation settings**:
    a. *Simulation time resolution*: 1 hour.
    b. *Solver*: GUROBI.
    c. *MILP gap*: 1%.
    d. *Unit Commitment Optimality*: integer.
    e. *Chronology*: fitted (24 hr/day x 365 days/yr).
    f. *Stochastic method*: deterministic.

16. **Interconnectors**: for the definition of each interconnection lines, the following data are used:
    a. The Net Transfer Capacity (NTC) defined as the maximum flow that a *supply area* can export through its interconnection interfaces with neighbouring *supply areas*.
    b. Minimum (<0) and maximum (>0) flow parameters for bidirectional lines is determined by utilizing ESKOM's data of surge impedance loading. For unidirectional lines, only the maximum flow is specified, with the minimum set to zero (in the model the flow it is constraint to export only from inner to outer regions).

2.2.2.4 - Generators parameters

This section reports the parameters considered to characterize the models of the generators and BESS:

Facility	Parameters
 NUCLEAR PLANT	• **Min Stable Level**: 95 % • **Must run**: On
 ESKOM GAS TURBINE	• **Maximum CF**: 5 %/year (due to gas shortage) • **Min Stable Level**: 35% • **Min Time Off/On**: 1 h
 PUMPED STORAGE	• **Eff**: 77.9% (roundtrip) • **Dispatching conditions**: received by ESKOM, in terms of minimum dam level and filling level requirements.
 WIND AND PV PLANTS	• **Min Annual CF**: 90% or 100%, depending on the scenarios
 HYDRO RESERVOIR	• **Two approaches for dispatching:** 1. Hourly production profiles made available from ESKOM 2. Modelling of dam capacity and natural inflow and optimization of the production profile.
 CSP PLANTS	• **Production profiles**: Eskom Data • **Curtailment**: NO
 BESS	• **Charge Eff**: 94% • **Discharge Eff**: 94% • **Simultaneous charge and discharge**: not allowed • **Min/Max SOC: 0%/100%, this is because** the capacity to be simulated is intended as the useful desired nominal capacity to be guaranteed at the connection point.
 RMIPPPP PLANTS	• **Operation**: from 5 a.m to 09:30 p.m • **Min CF**: 50 %/day • **Min Stable Level**: 35% • **Min Time Off/On**: 1 h
 COAL PLANTS	• **Min Stable Level**: 45% • **Min Up Time**: 8 h • **Min Down Time**: 8 h

2.3 - Supply Areas models (according to GCCA 2024)

2.3.1 - Western Cape

The Western Cape is located in the south-western part of South Africa and has Cape Town as its capital and main economic hub. The Western Cape transmission network is linked to the Northern Cape though two interconnections: the first one along the West Coast, while the second stretches over 550 km from the south-west of the supply area up to the north-east border.

The reference energy model of the supply area is represented in Figure 2-4.

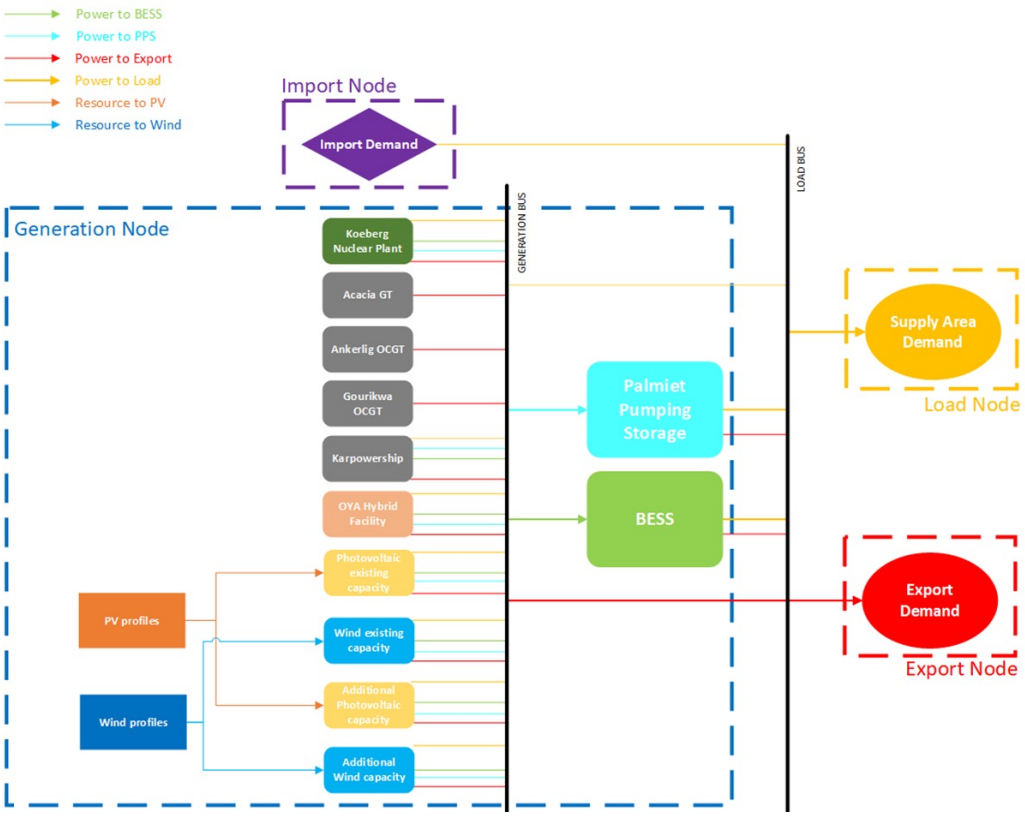


Figure 2-4: Western Cape reference energy model

The expected demand for 2025 has a peak of 3824 MW, while the NTC limit has been fixed to 4000 MW. The generators of the area are as follows:

- **Koeberg Nuclear Plant**: This is the unique base load plant in the supply area. It is characterized by two units of 950 MW, for a total power of 1900 MW. In agreement with ESKOM, the operation of the units shall be guaranteed for all the days of the years (no shutdown is admissible), and a minimum stable level of 95% (i.e., 902 MW for each unit) is set, to exclude any type of load-following behavior.
- **Gas-peaking plants**: The rigid operation of the nuclear plant is counterbalanced by the operation during the peak demand of the gas-based plants: the three OCGT of Ankerlig, Gourikwa and Acacia. Their operation is used only to satisfy the export demand of the supply area in accordance with the constraints mentioned in the previous chapter: annual CF of 5% and minimum stable level of 35%. Table 2-1 represents the characteristics of each of these plants.

Plant	Units	Unit Power (MW)	Total power (MW)	Minimum Stable Level (MW)
Acacia	3	57	171	60
Ankerlig	9	148	1332	466
Gourikwa	5	148	740	259

Table 2-1: Gas-based plants characteristics – Western Cape

- **Karpowership**: The Karpowership Power Plant is a 320MW gas fired power project aimed to generate power on floating gas ships on the coast of Saldanha. The 20-year contract is part of the South African government's Risk Mitigation Independent Power Producer Procurement Programme (RMIPPPP) emergency power procurement initiative, and it is subjected to the following RMIPPPP conditions: this plant must guarantee its availability between 5:00 a.m. and 09:30 p.m., and a minimum daily Capacity Factor (CF) of 50% within the time-window providing energy to satisfy both the supply area load and export demand.
- **Palmiet Pumped Storage scheme**: The Palmiet Pumped-Storage Scheme is located in the Kogelberg Nature Reserve in the Western Cape, near Grabouw. It is a collaborative project between Eskom and the Department of Water Affairs and Forestry. The power station operates with two units, each producing 200 MW, resulting in a total peak power delivery of 400 MW. Its primary function is to supply power to the Eskom national grid while also fulfilling the role of frequency and voltage regulation. The water flows from an upper reservoir to the machines located in an underground power station. Subsequently, the water is collected in a lower reservoir and pumped back to the upper reservoir during off-peak periods. The storage capacity is set equal to 10 GWh[7], value calculated from the capacity of the lower reservoir. The plant has a round trip efficiency of 77.9 % and it is characterized by some technical constraints that influence its operation in terms of minimum dam level and filling level requirements:
  - The upper dam should be full (56 unit generating hours) at 06:00 on each Monday morning.
  - The minimum top dam level is 8 Unit Generating Hours.
- **Oya Energy Hybrid facility**: this facility belongs to the RMIPPPP and it is based on the hybrid operation of wind turbines, solar PV arrays and Lithium-Ion batteries. These technologies are managed through a hybrid controller which organizes all three technologies to provide dispatchable power in accordance with the 128 MW of contracted power[8]. The plant, belonging to the RMIPPPP, operates between 5:00 a.m. and 09:30 p.m. and a minimum daily Capacity Factor (CF) of 50% within the time-window. At the same time, being it a RES plant, its merit order has been considered the same as of PV and Wind pants.
- **Existing PV plants**: Eight (8) IPP PV plants are already installed in WC, for a total installed power of 358.8 MW. As said, the production profile of the aggregated plants is calculated as weighted average of the profiles provided by ESKOM for each of them. The resulting profile is characterized by an average CF of 25%. The characteristics of each of the plants are reported in Table 2-2.

[7] *Eskom. Palmiet-PUMPED STORAGE SCHEME.* https://www.eskom.co.za/wp-content/uploads/2022/04/Palmiet_Pumped_Storage_Scheme_Technical_information_-_P_1-8.pdf
[8] *OYA Energy website* https://oya.energy/wind-solar-hybrid-project-about-oya/

Plant	Power (MW)	Station	Year	Status
Vredendal	8.8	Juno	2014	Operational
Aurora	9	Aurora	2015	Operational
Touwsrivier Project	36	Bacchus	2015	Operational
SlimSun Swartland Solar Park	5	Aurora	2016	Operational
Electra Capital (Pty) Ltd	75	Aurora	2017	Operational
Grootfontein PV 1	75	Kappa	2023	Awarded
Grootfontein PV 2	75	Kappa	2023	Awarded
Grootfontein PV 3	75	Kappa	2023	Awarded

Table 2-2: Existing PV plants characteristics - Western Cape

- **Existing Wind plants**: Western Cape is one of South Africa's ideal locations for wind energy projects. Seventeen (17) wind projects are already in operation for a total installed power of 1898 MW. Also in this case the total profile is calculated as weighted average of the data available, for a resulting annual CF of 47%.

Plant	Power (MW)	Station	Year	Status
Hopefield Wind Farm	65.4	Aurora	2014	Operational
Dassiesklip Wind Energy Facility	27	Bacchus	2014	Operational
Noblesfontein	75	Droerivier	2014	Operational
West Coast 1	94	Aurora	2015	Operational
Sere Wind Farm	100	Juno	2015	Operational
Gouda Wind Facility	138	Muldersvlei	2016	Operational
Excelsior Wind	31.9	Bacchus	2020	Committed
Perdekraal East	107.7	Kappa	2020	Committed
Karusa Wind Farm	139.8	Komsberg	2020	Committed
Roggeveld	140	Komsberg	2020	Committed
Soetwater Wind Farm	139.4	Komsberg	2020	Committed
Beaufort West Wind Facility	140	Droerivier B	2023	Awarded
Trakas Wind Facility	140	Droerivier B	2023	Awarded
Brandvalley Wind Farm	140	Komsberg	2023	Awarded
Rietkloof Wind Farm	140	Komsberg	2023	Awarded
Rietrug Wind Facility	140	Koring	2023	Awarded
Sutherland Wind Facility	140	Koring	2023	Awarded

Table 2-3: Existing Wind plants characteristics - Western Cape

- **Upgradable S/S capacity**: in accordance with the hypotheses explained in section 2.2.3, the total upgradable capacity in WC is 18.9 GW, disaggregated as follows:

Local Area	Substation	Trfr. Limit (MW)	Available Cap. if reinforced (MW)
Greater Komsberg	Komsberg	250.8	725.8
	Kappa	14	964
	Koring	195	1145
Greater Peninsula	Stikland	1068	1543
	Aurora	594.6	1069.6
	Acacia	1771	1771
	Pinotage	1096	1571
	Muldersvlei	1308	1308
	Bacchus	1092	1567
	Sterrekus	-	-
	Philippi	1226	1701
Western Cape	Droerivier	311.25	1380
	Droerivier B	195	1145
	Proteus	1189	1664
Northern Cape	Juno	152	1348.84
		76	

Figure 2-5. Upgradable transformers capacity in WS S/Ss

The plants that are outside the scope of the study are:

- **Cape Town plants**: The supply area is characterized by three additional plants: Steenbras Pumped-Storage Scheme and the Power Stations of Athlone and Roggebaai. Steenbras Pumped-Storage Scheme is a City of Cape Town (CoCT) generating facility. It consists of 4 x 45 MW units and is integrated into the CoCT network. Athlone and Roggebaai power stations are two gas turbine stations, which are owned and operated by the CoCT, and with an installed power of respectively 36 MW and 42 MW. They are used to generate electricity over much shorter periods, as they use much more expensive fuel. These plants **are excluded** from the current study as the available data on the load of the supply area are already net from their production and their management is not under the ESKOM control. At the same this study can provide useful outputs also for the management of their future dispatch.
- **Rooftop PV**: The City of Cape Town is encouraging the installation of private rooftop solar PV systems[9]. This initiative can have an influence on the magnitude of the peaks of the demand in the next years, considering that the self-production of the prosumers could decrease the net demand during the peak production. Their future energy production is not taken into account, supposing a not relevant magnitude of the installed power and the lack of data about the possible development of the latter. At the same time, as future perspective, the analysis of the effects of the development of the rooftop PV systems in the city could be a matter of interest.

[9] *"ROOFTOP SOLAR PV: GUIDELINES FOR SAFE AND LEGAL INSTALLATIONS IN CAPE TOWN" - Brochure*

2.3.2 - Eastern Cape

The Eastern Cape is South Africa's second-largest province by landmass and is located on the country's south-eastern coast. Due to its excellent and desirable wind energy sources, the Eastern Cape has attracted a significant share of the wind projects procured to date in the country. Solar resource is being considered by IPPs just to a minor extent, 75MW against more than 2GW of wind capacity installed. For this reason, as per ESKOM's request, only new wind capacity installations are evaluated in the study.

Figure 2-6 represents the reference energy model of the supply area.

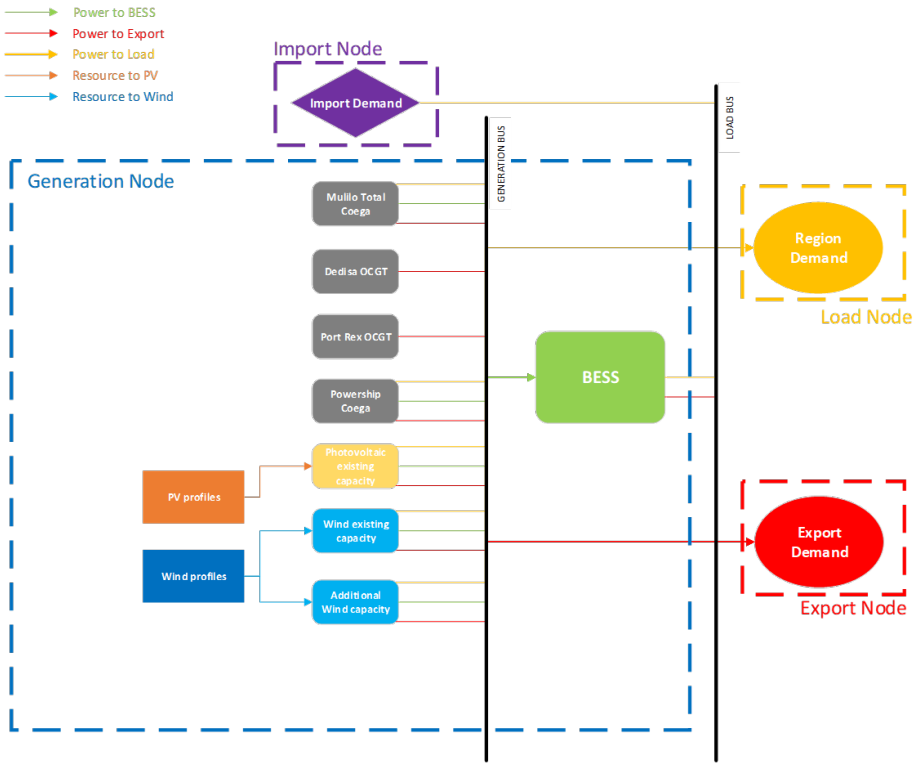


Figure 2-6: Eastern Cape reference energy model

The expected demand for 2025 has a peak of 1718 MW, while the NTC limit is fixed to 2773 MW. The generators of the area are resumed as follows:

- **Gas-peaking plants**: Two gas peaking plants are installed in the region: Port Rex OCGT and Dedisa OCGT, the latter in operation since 2015. Their operation is used only to satisfy the export demand of the supply area in accordance with the constraints mentioned in the previous chapter: annual CF of 5% and minimum stable level of 35%. The characteristics of both the plants are listed in the Table 2-4.

Plant	Units	Unit Power (MW)	Total power (MW)	Minimum Stable Level (MW)
Port Rex OCGT	3	57	171	60
Dedisa OCGT	2	167.5	335	117

Table 2-4: Gas-based plants characteristics – Eastern Cape

- **RMIPPPP gas plants**: Two gas plants belonging to the RMIPPPP are installed in the supply area: Powership Coega and Mulilo Total Coega. They have been awarded in 2022 and are characterized by a contracted capacity of respectively 450 MW (min stable level 157.5 MW) and 197.76 MW (min stable level 69.2 MW), and subject to the above-mentioned RMIPPP operational constraints. Mulilo Total Coega plant is characterized by the hybrid operation of 216 MW of PV panels and 197.76 MW of Gas Engines.
- **Existing PV plants**: The supply area counts a unique PV plant of 75 MW, constructed under the Ruigtevallei station and operational since 2015.
- **Existing Wind plants**: Twenty-one (21) wind projects are expected to be operational in 2025 in the supply area for a total installed capacity of 2029 MW and an average annual CF of 46%.

Plant	Power (MW)	Station	Year	Status
MetroWind Van Stadens Wind Farm	26.19	Grassridge	2014	Operational
Jeffreys Bay	138	Grassridge	2014	Operational
Dorper Wind Farm	100	Delphi	2015	Operational
Red Cap Kouga Wind Farm - Oyster Bay	80	Grassridge	2015	Operational
Grassridge Wind Farm	60	Grassridge	2015	Operational
Cookhouse	140	Poseidon	2015	Operational
Tsitsikamma Community Wind Farm	94.8	Grassridge	2016	Operational
Chaba Wind	20.6	Pembroke	2016	Operational
Amakhala Emoyeni (Phase 1) Eastern Cape	140	Poseidon	2016	Operational
Waainek	23.86	Poseidon	2016	Operational
Red Cap - Gibson Bay	110	Grassridge	2017	Operational
Nojoli Wind Farm	87	Poseidon	2017	Operational
Oyster Bay Wind Farm	140	Grassridge	2020	Committed
Wesley-Ciskei Wind Project	32.7	Pembroke	2020	Committed
Nxuba Wind Farm	138.9	Poseidon	2020	Committed
Golden Valley Wind	117.72	Poseidon	2020	Committed
Dassiesridge Wind Farm[10]	75	Grassridge	2022	Awarded
Wolf Wind Farm	84	Grassridge	2023	Awarded
Coleskop WEF	140	Koruson	2023	Awarded
Phezukomoya WEF	140	Koruson	2023	Awarded
San Kraal WEF	140	Koruson	2023	Awarded

Table 2-5: Existing Wind plants characteristics - Eastern Cape

[10] *This plant belongs to the RMIPPPP programme. Since we do not have information on its dispatching, we assume that ESKOM would dispatch it in accordance with its rating power calculated on 75 MW basis.*

- **Upgradable S/S capacity**: in accordance with the hypotheses explained in section 2.2.3, the total upgradable capacity in EC is 7.7 GW, disaggregated as follows:

Local Area	Substation	Trfr. Limit (MW)	Available Cap. if reinforced (MW)	
Gqeberha	Grassridge	368	843	
		144		
	Dedisa	424	899	
Eastern Cape	Neptune	988	1463	
	Delphi	247.5	1435	
	Pembroke	475	1425	
	Pembroke	465	465	→ Not upgradable
	Poseidon	-	120.5	
		0		
		120.5		→ Not upgradable (taken only the Trfr. @132 kV out)
		93		
		38		
Hydra	Ruigtevallei	60	60	
		40		→ Not upgradable (taken only the Trfr. @132 kV out)
	Koruson ("old" Hydra D)	55	1005	

Figure 2-7. Upgradable transformers capacity in ES S/Ss

2.3.3 - Northern Cape

The Northern Cape is a province located in the western part of South Africa. The region consists of vast expanses of land with excellent solar radiation and wind resources, making it an attractive location for V-RES, with a high concentration of PV plants. Given the abundance of solar resource and less interest in wind in the area, two cases are simulated:

1. PV and Wind.
2. Only PV.

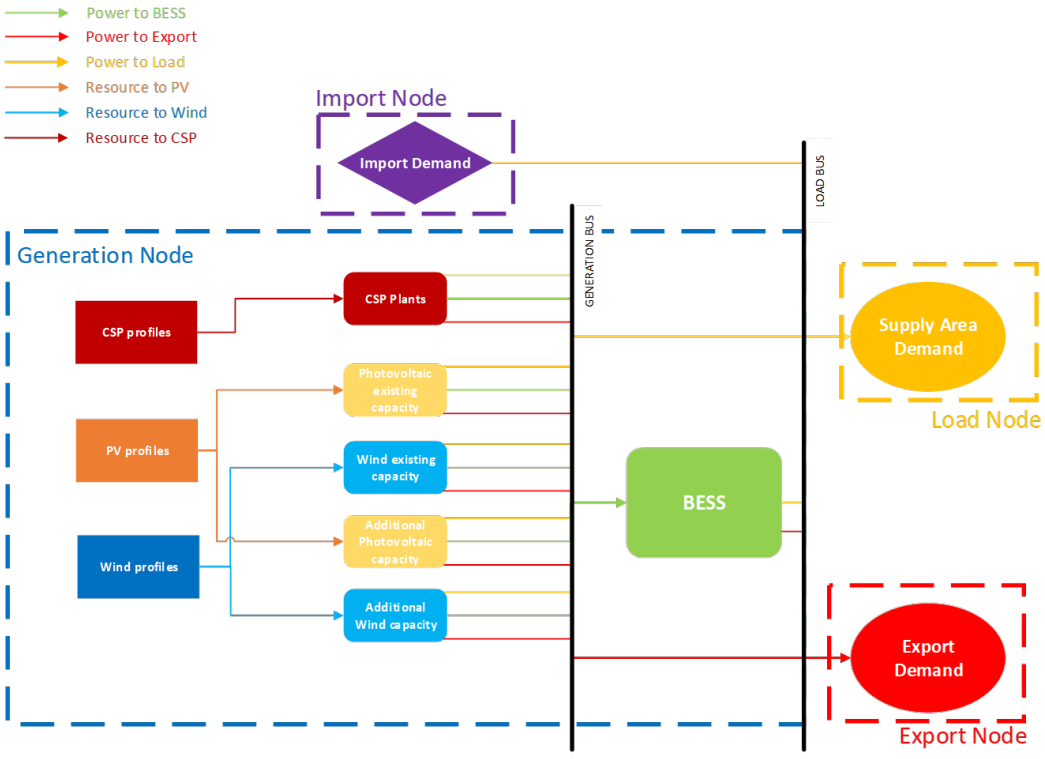


Figure 2-8: Northern Cape reference energy model

The expected demand for 2025 has a peak of 1045 MW, while the NTC limit is fixed to 2815 MW. Also, the load profile is already net of the 10 MW Neusberg Hydro Project. The generators installed in the supply area are listed:

- **CSP plants**: The supply area on Northern Cape is the one characterized by the highest solar irradiance in all the country. This condition has made the Northern Cape a promising area for the installation of Concentrated Solar Power (CSP) plants. Six CSP plants are installed in the supply area with the addition of the Redstone Solar Thermal Power Plant that starting from the end of 2023 will make the total installed power for this technology equal to 600 MW.

Plant	Power (MW)	Station	Year	Status
KaXu Solar One	100	Paulputs	2015	Operational
Bokpoort CSP Project	50	Garona	2016	Operational
Khi Solar One	50	Upington	2016	Operational
XiNa Solar One	100	Paulputs	2018	Operational
Kathu Solar Park	100	Ferrum	2019	Committed
Redstone Solar Thermal Power Plant	100	Olien	2019	Committed
Ilanga CSP 1 / Karoshoek Solar One	100	Upington	2019	Operational

Table 2-6: Existing CSP plants characteristics – Northern Cape

These plants are modeled in the simulation in a single equivalent node, with the aggregated profile calculated on the basis of the profiles provided by ESKOM. The CSP of Redstone is not yet commissioned and hence no production profile is available yet: it is agreed upon with ESKOM to take the rating profile of Bookport, which is the one with the highest thermal capacity (~9hrs), similar to Redstone (12hrs). The position of Bookport is not close to Redstone, but being NC characterized by an almost constant irradiation over the whole area, this is not expected to significantly impact on the results.

- Existing PV plants: thirty-three (33) Solar systems are expected in the region by 2025, with the total power that amounts to 2051 MW characterized by an average CF equal to 26%.

Plant	Power (MW)	Station	Year	Status
Aries Solar	9.65	Aries	2014	Operational
Droogfontein Solar PV Project	48.25	Boundary	2014	Operational
Vredendal	8.8	Juno	2014	Operational
Greefspan PV Power Plant	10	Kronos	2014	Operational
Lesedi Power Company	64	Olien	2014	Operational
Herbert PV Power Plant	19.93	Olien	2014	Operational
Konkoonsies Solar	9.65	Paulputs	2014	Operational
Upington Solar PV	8.9	Upington	2014	Operational
Boshoff Solar Park	60	Boundary	2015	Operational
Kathu Solar Energy Facility	75	Ferrum	2015	Operational
Sishen Solar Facility	74.4	Ferrum	2015	Operational
Mulilo Renewable Energy Solar PV Prieska	20	Kronos	2015	Operational
Jasper Power Company	75	Olien	2015	Operational
Pulida Solar Park	75	Boundary	2016	Operational
Mulilo Sonnedix Prieska PV	75	Kronos	2016	Operational
Adams Solar PV 2	75	Ferrum	2017	Operational
Mulilo Prieska PV	75	Kronos	2017	Operational
Aggeneys Solar	40	Aggeneis	2020	Committed
Droogfontein Solar Park	75	Boundary	2020	Committed
Loeriesfontein Orange	75	Helios	2020	Committed
Greefspan PV Power Plant No. 2	55	Kronos	2020	Committed
Konkoonsies II Solar	75	Paulputs	2020	Committed
Sirius Solar PV Project One	75	Upington	2020	Committed
Dyason's Klip 1	75	Upington	2020	Committed
Dyason's Klip 2	75	Upington	2020	Committed
ACWA Power Project DAO	150	Garona	2022	Awarded
Gemsbok PV2[11]	197.76	Nieuwehoop	2022	Awarded
Scatec Kenhardt PV 1[11]	50	Nieuwehoop	2022	Awarded
Scatec Kenhardt PV 2[11]	50	Nieuwehoop	2022	Awarded
Scatec Kenhardt PV 3[11]	50	Nieuwehoop	2022	Awarded
Avondale 1 Solar Park[11]	75	Upington	2022	Awarded
Graspan Solar PV Project	75	Boundary	2023	Awarded
Waterloo Solar Park	75	Mookodi	2020	Committed

Table 2-7: Existing PV plants characteristics – Northern Cape

[11] *These are plants belonging to the RMIPPPP programme. They are modelled as normal PV plants by using the rating factor received by ESKOM. This assumption stands on the following considerations:*

1. *For hybrid PV+BESS plant, since the plant must be dispatchable during the 05:00-21:30 time window, BESS should be ready during the day, and therefore it is reasonable to consider their production as 0 during the night hours to maximise BESS availability in the time window. Since we do not have information on the dispatching of these plants during the daily hours, we assume that ESKOM would dispatch it in accordance with their rating powers.*
2. *For hybrid PV+gas plant, given gas shortage, it is reasonable that the plant is dispatched according to the available power of PV, using gas only in case of need, especially during the ramping hours.*

- **Existing Wind plants**: Seven (7) wind projects already exist in the supply area for a total installed capacity of 874.6 MW and an average annual CF of 46%.

Plant	Power (MW)	Station	Year	Status
Sere Wind Farm	100	Juno	2015	Operational
Khobab Wind	138	Helios	2018	Operational
Loeriesfontein 2 Wind Farm	138	Helios	2018	Operational
Kangnas	136.7	Groeipunt	2020	Operational
Copperton Wind Farm	102	Kronos	2020	Operational
Garob Wind Farm	135.9	Kronos	2020	Operational
Dwarsrug Wind Facility	124	Helios	2023	Operational

Table 2-8: Existing Wind plants characteristics – Northern Cape

- **Upgradable S/S capacity**: in accordance with the hypotheses explained in section 2.2.3, the total upgradable capacity in NC is 15.2 GW, disaggregated as follows:

Local Area	Substation	Trfr. Limit (MW)	Available Cap. if reinforced (MW)	
Greater Namaqualand	Aggeneis	64	0	V_{out} < 132 kV
		177	1425	
	Gromis	162	1425	
		79	0	V_{out} < 132 kV
	Groeipunt	101	101	Not upgradable (taken only the Trfr. @132 kV out)
	Paulputs	98	1166.3	
	Oranjemond	175	0	V_{out} < 132 kV
	Nama	163	0	V_{out} < 132 kV
	Upington	68	1018.1	
	Nieuwehoop	366	1078	
	Aries	34	1416.45	Upgradable by adding 1500 MVA 400/132 kV Trfrs.
Northern Cape	Kronos	85	973	
	Olien	219	219	Not upgradable (taken only the Trfr. @132 kV out)
	Ferrum	1253	1253	Not upgradable (taken only the Trfr. @132 kV out)
		288	0	V_{out} < 132 kV
	Garona	778	1253	
	Lewensaar	72	0	V_{out} < 132 kV
	Boundary	248	248	Not upgradable (taken only the Trfr. @132 kV out)
	Helios	2	951.75	
		43		
	Juno	152	1348.84	
		76		
	Mookodi	432	1382	

Figure 2-9. Upgradable transformers capacity in NC S/Ss

2.3.4 - Hydra Cluster

The Hydra Cluster does not correspond to a Province of the country, but it is an electrical supply area shared between Northern Cape, Western Cape, Eastern Cape and Free State Provinces. The area is characterized by the presence of two reservoir-based hydropower plants and a total capacity of 1279 MW of Wind and Solar capacity.

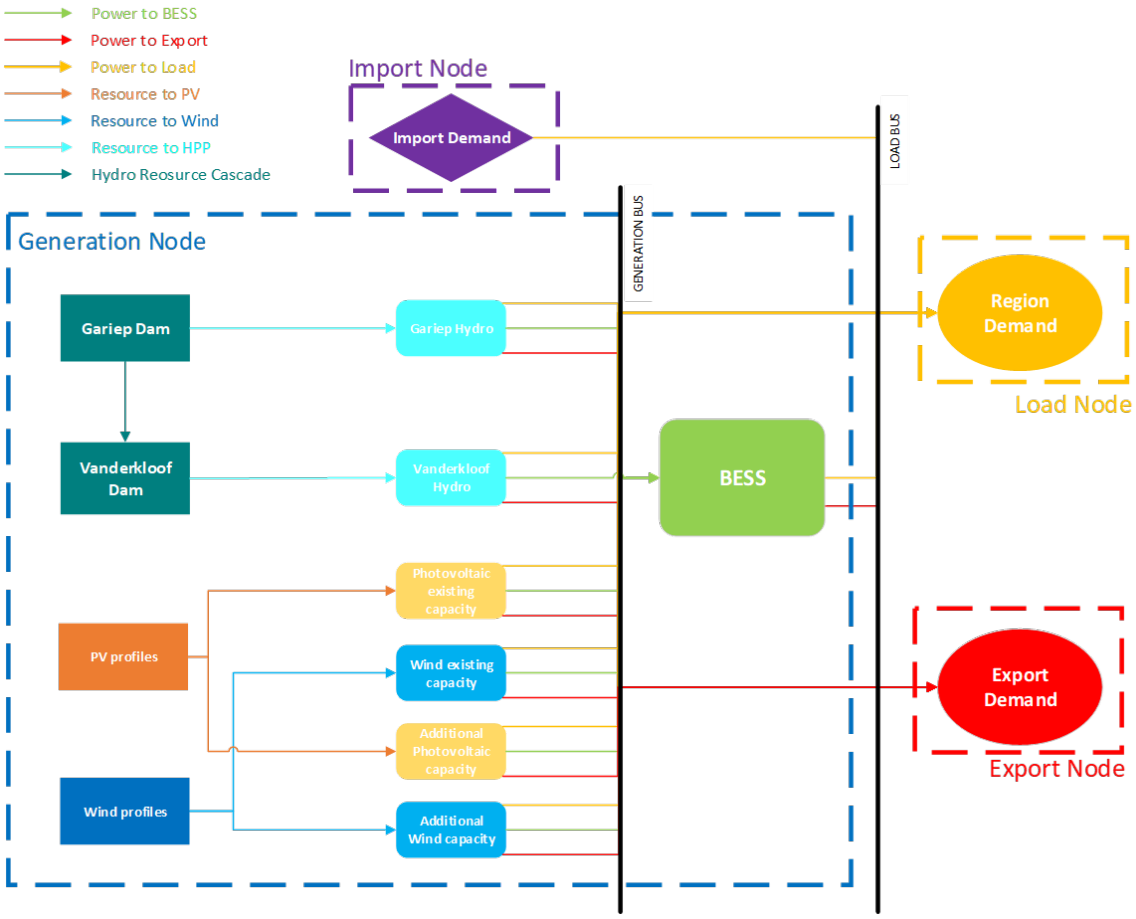


Table 2-9: Hydra Cluster reference energy model

The expected demand for 2025 has a peak of 204 MW, while the NTC limit has been fixed to 2881 MW. The area is characterized by the presence of two hydropower plants:

- **Gariep Hydroelectric Power Station**: The Gariep Hydroelectric Power Station is a major hydroelectric power generation facility situated on the Orange River in the Free State province. With a total installed capacity of 360 megawatts (MW) shared between four units, the power station operates by harnessing the flow of water from the Gariep Dam, which is the largest dam in South Africa. The dam's reservoir, created by the damming of the Orange River, serves multiple purposes, including irrigation, water supply, and flood control.
- **Vanderkloof Hydroelectric Power Station**: The Vanderkloof Hydroelectric Power Plant is another significant hydroelectric power generation facility. It is situated on the Orange River at approximately 130 km downstream from Gariep Dam. With 240 MW shared between two units, the Vanderkloof Hydroelectric Power Plant harnesses the flow of water from the Vanderkloof Dam to generate electricity. The Vanderkloof Dam, like the Gariep Dam, serves various purposes, including irrigation, water supply, and flood control.

- The hourly profiles of both the hydro plants for 2021 and 2022 have been provided by ESKOM. Comparing the data with the historical monthly measurements of the dams' outflow, the profile of the year 2021 has been considered as the most representative of the historical trend. A comparison between the actual dispatch of the hydro plants (Scenario B) and the optimized one (Scenario A) is modelled, obtained using the technical data and the historical natural inflow trend, has been done.
    - SCENARIO A: Flow rate into Gariep based on time series of data from Bethulie station (data available up to 1970)[12].
    - SCENARIO B: production profiles of Gariep and Vanderkloof from Eskom.
- **Existing PV plants**: nine (9) Solar systems are expected in the region by 2025, with the total power that amounts to 535 MW characterized by an CF equal to 26%.

Plant	Power (MW)	Station	Year	Status
Project Dreunberg	75	Ruigtevallei	2015	Operational
Mulilo Renewable Energy Solar PV De Aar	10	Hydra	2014	Operational
Kalkbult	75	Hydra	2014	Operational
Linde	36.8	Hydra	2014	Operational
De Aar Solar PV	48.25	Hydra	2015	Operational
Solar Capital De Aar	75	Hydra	2015	Operational
Solar Capital De Aar 3	75	Hydra	2016	Operational
Mulilo De Aar Hybrid	75	Hydra	2022	Awarded
Du Plessis Dam PV 1	75	Hydra	2023	Awarded

Table 2-10: Existing PV plants characteristics – Hydra Cluster

- **Existing Wind plants**: six (6) wind projects will be already installed in 2025 in the supply area for a total installed capacity of 734 MW and an average annual CF of 47%.

Plant	Power (MW)	Station	Year	Status
Noupoort Mainstream Wind	79	Hydra	2016	Operational
Longyuan Mulilo De Aar Maanhaarberg Wind Energy Facility	96	Hydra	2018	Operational
Longyuan Mulilo De Aar 2 North Wind Energy Facility	139	Hydra	2018	Operational
Coleskop WEF	140	Koruson	2023	Awarded
Phezukomoya WEF	140	Koruson	2023	Awarded
San Kraal WEF	140	Koruson	2023	Awarded

Table 2-11: Existing Wind plants characteristics – Hydra Cluster

- Upgradable S/S capacity: in accordance with the hypotheses explained in section 2.2.3, the total upgradable capacity in HC is 1.3 GW, disaggregated as follows:

[12] https://www.dws.gov.za/Hydrology/Verified/hymain.aspx

Local Area	Substation	Trfr. Limit (MW)	Available Cap. if reinforced (MW)
Hydra Cluster	Hydra	108	198
		90	
		49	
	Roddekuil	60	60
	Koruson ("old" Hydra D)	55	1005
	Ruigtevallei	60	60
		40	

Not upgradable (taken only the Trfr. @132 kV out)

Not upgradable (taken only the Trfr. @132 kV out)

Not upgradable (taken only the Trfr. @132 kV out)

Figure 2-10. Upgradable transformers capacity in NC S/Ss

Nevertheless, it shall be noted that according to ESKOM, expected new S/S capacity is planned in "new" Hydra D, Hydra B, and Gamma to be added to this 1.3 GW.

2.4 - Supply Areas models (according to GCCA 2025)

2.4.1 - North West

North West is a province of South Africa surrounded by Northern Cape, Free State, Mpumalanga, and Limpopo. Much of the province consists of flat areas of scattered trees and grassland. The area is characterized by a high PV capacity and a very low wind potential. Given the abundance of solar resource and low interest for wind in the area, only solar is simulated as candidate additional capacity.

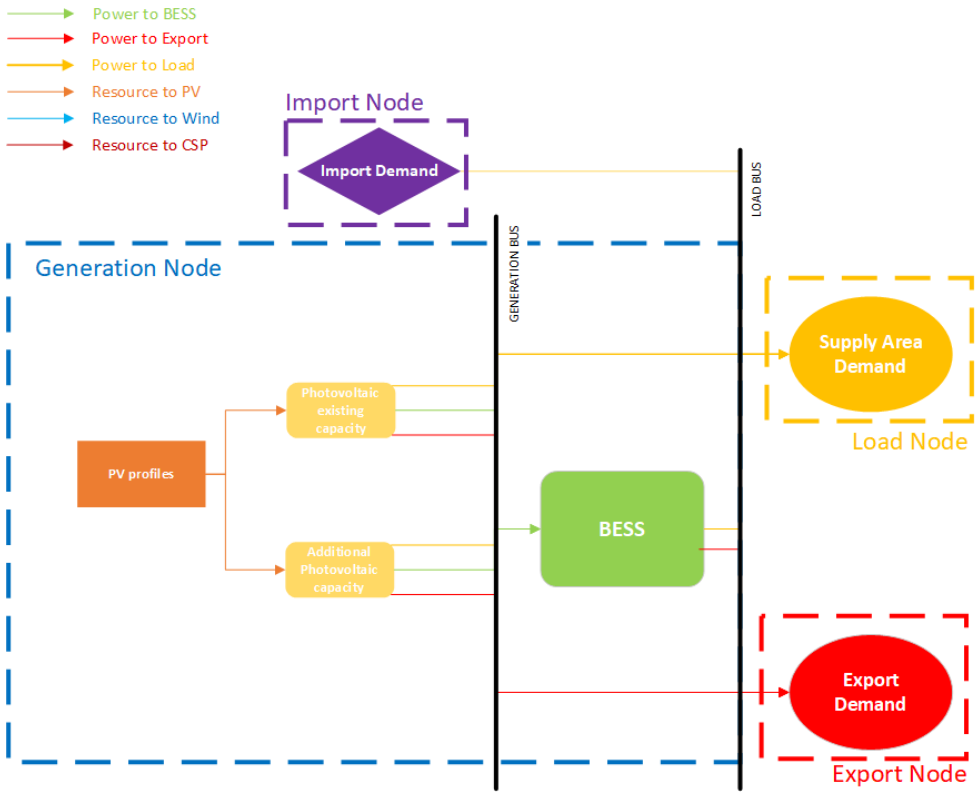


Figure 2-11. North West reference energy model

The expected demand for 2025 has a peak of 3229 MW while the NTC limit has been fixed to 2897 MW. The area is characterized by:

- **Existing PV plants**: twenty-four (24) Solar systems are expected in the region by 2025, with the total power that amounts to 1639.9 MW with an average CF equal to 25%.

Plant	Power (MW)	Station	Year	Status
RustMo1 Solar Farm	7	Bighirn	2014	Operational
Blyvoor Solar	10	Carmel	2024	BQ
Chemwes Solar Park	15	Hermes	2024	BQ
Doornhoek 1 PV Facility	120	Hermes		Awarded
Buffels Solar PV Project	75	Hermes	2024	BQ
Noko Solar Power Plant (RF)(Pty)Ltd	100	Hermes	2024	BQ
Bokamoso Solar Park	67,9	Mercury	2020	Operational
Adara 2 Solar Project	40	Mercury	2024	BQ
Lion Thorn 40MW Solar Plant	40	Mercury	2024	BQ
Phofu Solar Power Plant	100	Mercury	2024	BQ
Thakadu Solar Power Plant (RF)(Pty)Ltd.	100	Mercury	2024	BQ
Sibanye Gold Solar PV Project	50	Midas	2024	BQ
Zeerust Solar Park	75	Watershed	2020	Operational
Boitumelo Solar Power Plant (RF)(Pty)Ltd	150	Watershed	2024	Awarded
Kutlwano Solar Power Plant	150	Watershed	2024	Awarded
BUFFELSPOORT SOLAR PROJECT	30	Watershed	2024	BQ
Dudfield Solar	50	Watershed	2024	BQ
Kalgold Solar Park	15	Watershed	2024	BQ
Leeumax 15MW PV	15	Watershed	2024	BQ
Lerato Solar Power Plant	120	Watershed	2024	BQ
Lichtenburg 1 PV	100	Watershed	2024	BQ
Lichtenburg 2 PV	100	Watershed	2024	BQ
Lichtenburg 3 PV	100	Watershed	2024	BQ
PPC Slurry Solar PV 1	10	Watershed	2024	BQ

Table 2-12. Existing PV plants characteristics – North West

- Rooftop PV plants: the installed capacity, based on the latest analysis of the regional data is 669.3 MW.

2.4.2 - Free State

Free State is a province in the center of the country surrounded by Northern Cape, North West, Gauteng, Mpumalanga, Lesotho, and Eastern Cape. The province is a highland, with almost all land being 1000 meters above sea level. The area is characterized by a high PV capacity and a very low wind potential. Given the abundance of solar resource and low interest for wind in the area, only solar is simulated as candidate additional capacity.

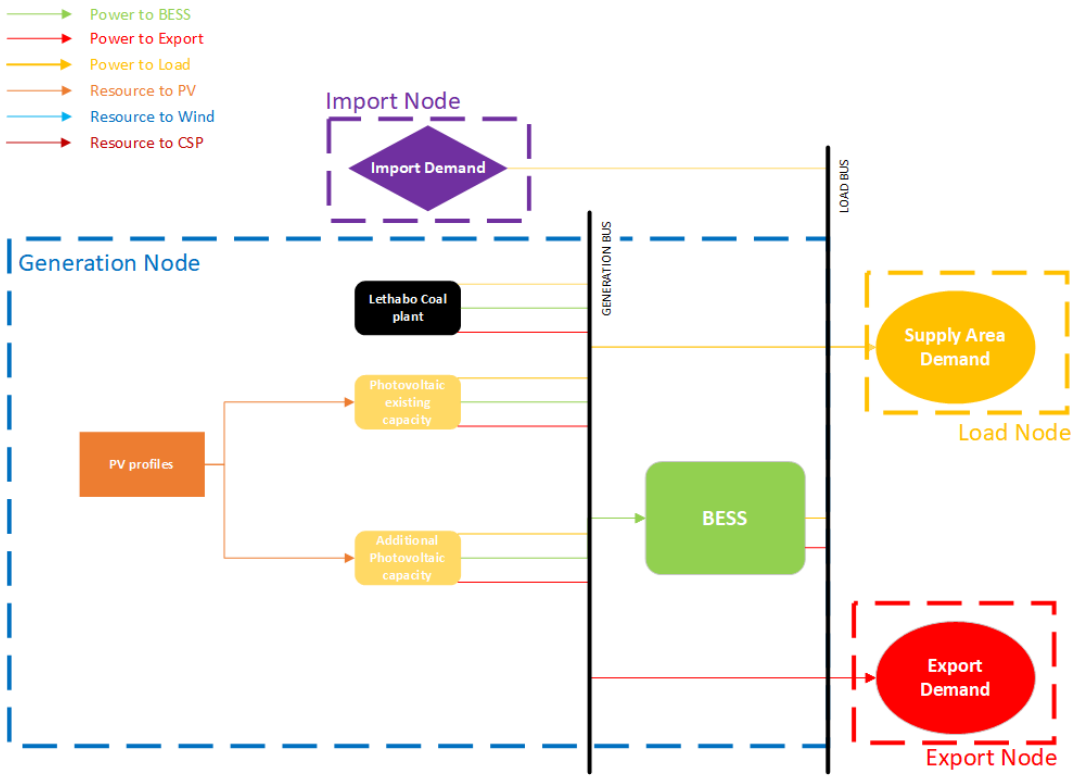


Figure 2-12. Free State reference energy model

The expected demand for 2025 has a peak of 1328 MW while the NTC limit has been fixed to 2552 MW. The area is characterized by:

- **Coal plants**: a plant composed of six (6) units is installed in the region, the oldest being in operation since 1986. The capacity of each unit is 583 MW. The modelled operational constraints are: minimum stable level of 45%, minimum up time 8 hours and minimum down time 8 hours.
- **Existing PV plants**: seventeen (17) PV systems are expected in the region by 2025, with the total power that amounts to 1941 MW characterized by an average CF equal to 25%.

Plant	Power (MW)	Station	Year	Status
Braklaagte PV	75	Artemis	2023	Awarded
DPT Hennenman Solar Farm	20	Everest	2024	BQ
GOOD HOPE 2 SOLAR PARK 200 MW	200	Artemis	2024	Awarded
GROOTSPRUIT SOLAR PROJECT	75	Artemis	2023	Awarded
Kentanie PV	75	Artemis	2023	Awarded
Khauta South Solar PV Facility (RF)(Pty) Ltd	240	Leander	2024	BQ
Klipfontein PV	75	Artemis	2023	Awarded
Klipfontein PV 2	75	Artemis	2023	Awarded
Leliehoek PV	75	Harvard	2023	Awarded
Letsatsi Power Company	64	Harvard	2024	Operational
Ngonyama Solar	240	Artemis	2024	Awarded
SANNASPOS SOLAR PROJECT	75	Artemis	2023	Awarded
Sonneblom Solar Power Plant (RF)(Pty)Ltd	45	Harvard	2024	BQ
Sonoblomo PV	75	Leander	2023	Awarded
Sonvanger Solar Power Plant	142	Everest	2024	BQ
Springbok Solar Power Plant (RF)(Pty)Ltd	150	Everest	2024	BQ
Virginia 3 Solar Park	240	Theseus	2024	Awarded

Table 2-13. Existing PV plants characteristics – Free State

- **Rooftop PV plants**: the installed capacity, based on the latest analysis of the regional data is 280.2 MW.

2.5 - Interconnected Model (GCCA 2025)

In the *Interconnected* model, the six (6) *supply areas* previously modelled are interconnected and have the possibility to exchange energy (import/export) with each other. Moreover, four additional regions are introduced, corresponding to the *supply areas* of KwaZulu Natal (KN), Gauteng (GT), Limpopo (LI), and Mpumalanga (MP). They are modelled in PLEXOS as export nodes (sinks) with a regional load equal to the supply area capacity retrieved from the latest GCCA 2025.

With the increased complexity of the model, additional assumptions have been made and are detailed in the subsequent sections.

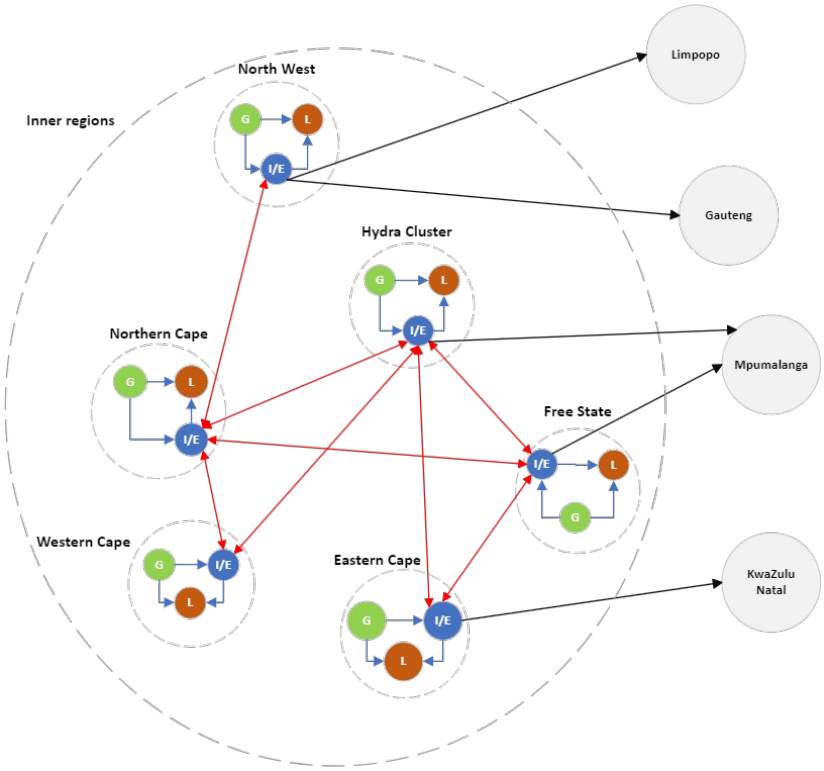


Figure 2-13. Interconnected reference energy model

A schematic version of the model is reported in Figure 2-13, to be read at the light of the following clarifications:

1. The internal lines (►) are virtual lines connecting the Generation G, Load L, and the Import/Export I/E nodes for the six inner regions (WC, NC, EC, HC, FS, NW).

2. The 8760 hrs load profile is given for the six inner regions (WC, NC, EC, HC, FS, NW). For the external regions, the load is modelled as a fixed value corresponding to the generation connection capacity of the regions in the GCCA 2025. Values are reported in Table 2-14.

Generation connection capacity (MW)			
KN	MP	LI	GT
5500	3320	3360	4680

Table 2-14. Generation connection capacity [MW] (GCCA 2025)

3. For each region, the maximum NTC is set, based on the updated data received by Eskom, and reported in Table 2-15.

Net Transfer Capacity (MW)					
WC	NC	EC	HC	FS	NW
3200	2244	900	2370	2552	2897[13]

Table 2-15. Net Transfer Capacity (NTC) [MW]

As it is visible, the area of EC is the most constrained. Despite the apparent limitation in value, this lower threshold is crucial for maintaining the internal security of operation of the area, even though it is expected to considerably limit the V-RES potential (both capacity and generation) of the area and, consequently, impact the overall model outcomes.

4. The lines between the inner regions (↔) and towards the exporting regions (→) do represent the physical corridors that interconnect the supply areas, and they are modelled by considering the limit of maximum flow represented by the surge impedance loading of each interconnection line expressed in megawatts (MW). All the corridors are physical, except for the interconnection from HC to MP. In the reality, this backbone is composed by three (3) 765 kV-corridors from HC to FS (Gamma S/S-Perseus S/S: 765 kV & Hydra S/S-Perseus S/S: 765 kV), FS to NW (Perseus S/S-Mercury S/S: 765 kV), and finally NW to MP (Mercury S/S-Zeus S/S: 765 kV). Nevertheless, given the limits of the Perseus S/S (in FS) and Mercury S/S (in NW) to evacuate power in/out the respective *supply area*, the backbone can be considered a direct corridor between HC and MP with a good and acceptable level of approximation. Table 2-16 reports the maximum admissible flow (bidirectional) on the interconnectors.

WC	WC-NC	483 MW
	WC-HC	3583 MW
NC	NC-WC	483 MW
	NC-HC	794 MW
	NC-NW	560 MW
	NC-FS	572 MW
EC	EC-HC	1796 MW
	EC-FS	921.5 MW
	EC-KN	1103 MW

HC	HC-WC	3583 MW
	HC-NC	794 MW
	HC-EC	1796 MW
	HC-FS	2019 MW
	HC-MP	2416.5 MW[14]
FS	FS-EC	921.5 MW
	FS-NC	572 MW
	FS-HC	2019 MW
	FS-MP	1458 MW
NW	NW-NC	560 MW
	NW-GT	2322 MW
	NW-LI	4714 MW

Table 2-16. Interconnections' max flow

[13] *This value is subject to the revamping of the Hera S/S and further internal reinforcements.*
[14] *It is the minimum Surge Impedance Loading between the segments Gamma-Perseus + Hydra-Perseus, Perseus-Mercury, and Mercury-Zeus.*

5. In the interconnected model, based on the GCCA 2025 hypotheses, rooftop PV systems existing in each *supply area* are incorporated as additional generators for WC, NC, EC, and HC (not considered in the GCCA 2024). This increases the overall generation capacity within these specific areas. The values, sourced from ESKOM and pertaining to October 2023, are outlined in the Table 2-17.

Installed rooftop PV (MW)					
WC	NC	EC	HC	NW	FS
527.4	129.5	368.2	0	669.3	280.2

Table 2-17. Installed rooftop PV capacity

6. In the GCCA 2024, the BQs were not classified as part of the existing capacity. However, in the GCCA 2025, they are considered as existing. Consequently, for WC, EC, and HC, the profiles and the installed capacity of existing PV/wind installations have been adjusted to include the BQ as well (No BQ are present in NC). This entails the incorporation of all the new plants and BQs as outlined in the latest version of the GCCA 2025, resulting in a modification of the overall generation fleet in the areas. The BQs added are reported in Table 2-18, Table 2-19, and Table 2-20 for the different *supply areas*.

Eastern Cape additional BQs		
Name	Technology	Capacity (MW)
Impofu East Wind Farm	Wind	111
Impofu North Wind Farm	Wind	111
Impofu West Wind Farm	Wind	111

Table 2-18. BQs GCCA 2025- Eastern Cape

Hydra Cluster additional BQs		
Name	Technology	Capacity (MW)
Du Plessis Dam Solar PV2	PV	75
Hartebeesthoek Wind Power	Wind	140
Mooi Plaats Solar PV Plant	PV	240
Mulilo De Aar 2 South Wind Energy Facility	Wind	140
Paarde Valley B PV2	PV	120
Sun Central 1 PV	PV	100
Sun Central 2 PV	PV	100
Sun Central 3 PV	PV	100
Ukuqala Solar PV	PV	75
Umsobomvu Wind Energy Facility	Wind	140

Table 2-19. BQs GCCA 2025- Hydra Cluster

Western Cape additional BQs		
Name	**Technology**	**Capacity (MW)**
FE Overberg	Wind	380
Darling Wind Power	Wind	10
Hartebeesr Wind Farm	Wind	100
Slimsun Too- Phase 2	PV	10
Witberg Wind Farm	Wind	120
Wolseley Wind Farm	Wind	123.9
Karreebosch Wind	Wind	140
Kudusberg 560 MW Wind Farm	Wind	320
Great Karoo Wind Farm	Wind	240
Sutherland 2 Wind Farm	Wind	140
Fe Berg River	PV	200
FE Bonne Esperance 140 MW	PV	140

Table 2-20. BQs GCCA 2025- Western Cape

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7. Considering the diverse natural resources across regions, their related potential, and the expected interest of IPPs based on the resource availability, two constraints are introduced for the newly proposed V-RES generation units:
   - In the case of PV, the condition sets that the newly added capacity in NC shall be 8% greater than the PV capacity in WC. This value is chosen in accordance with the proportion between the CFs of PV in the two areas, considering that investors may be inclined to invest more in regions where PV plants demonstrate higher productivity.
   - Regarding wind farms, recognizing the variability of suitable resource across the regions, the following constraint is introduced, as indicated by Eskom: a minimum of 60% of new wind installations shall be developed in WC, 30% shall be allocated in EC, and the remaining percentage designated for other *supply areas*. This distribution aims to guide the optimization towards the allocation of wind resources based on the regional capabilities and preferences.

8. Two scenarios are simulated: with and without a 2.46 GWh/0.615 GW BESS in FS and NW, that are expected to be procured and commissioned in 2/3 years.

9. Candidate BESS in WC vs NC vs HC vs EC: in the Interconnected model, we selected NC as the supply area to finally host the 2 GWh/0.5 GW BESS tested in all the *Standalone Supply Area*. The reason behind this modelling decision is two-fold:
   a. NC is the supply area targeted in the first round of the BESIPPPP for the procurement of the 513 MW BESS, aimed at unlocking the constrained grid capacity in the area.
   b. The standalone simulations (see section 3.1.5), and the overall system needs, indicated the following:
      i. NC is the area where BESS is utilized the most (cycles- and energy-wise) in case of no curtailment.
      ii. NC is the area where BESS allows the largest relative increment of additional V-RES that can be installed (in both cases of w/ and w/o curtailment).

iii. System balances and ROCOF needs in NC.
iv. In EC, HC, WC, being there available rotating capacity and less balancing/inertia problems, the curtailment outperforms the BESS advantages.

10. Concerning the substation (S/S) capacity, the limit for each S/S is updated to consider the latest GCCA 2025, based on the same hypotheses reported in section 2.2.3:

Supply Area	Total Max S/S capacity [MW]
EC	8 106
WC	17 593
NC	13 994
HC	5 212
FS	8 463
NW	8 383

Table 2-21. Total upgradable max S/S capacity for each supply area

11. With respect to the *Standalone Supply Area* simulations, the following modelling decisions are taken regarding the candidate additional V-RES capacity and the existing hydro fleet:
    - Wind is considered in NC, to increase the areas where potentially allocate and install wind, which is the resource with the most ambitious IRP-targets, but at the same time with the largest constraints in terms of space requirements, contrary to PV.
    - Since the hydro dispatching is not under control of Eskom and subject to water release constraints, the dispatching of Gariep and Vanderkloof hydro plants in HC is not optimized and the production profiles received from Eskom are directly inserted in PLEXOS.

12. In terms of curtailment scenarios, the same hypothesis adopted for the *Standalone Supply Area* model is kept, that is 10% for all existing and additional candidate V-RES. In fact, since the modelled *supply areas* are all far away from the load centers, curtailment is expected to be more convenient than building new lines for evacuating the additional capacity.

3 - RESULTS AND DISCUSSIONS

3.1 - Standalone Supply Areas (WC, NC, EC, HC) – GCCA 2024

For each supply area, the following outcomes are reported:

1. Additional Capacity [MW] of PV and wind that can be potentially installed in 2025, for each simulated scenario.
2. The net-export Duration Curves (DCs) of the resulting optimal dispatch in each scenario. The curve shows the hourly next export values, that is the total production in the area minus the total load consumption, sorted in descending order. The advantage in the use of an DC-kind representation is that it provides an overall overview on how many hours the energy production saturates the NTC, giving a representation of the effectiveness of V-RES integration in the area. The reported graphs also have dotted lines, which represent the net-export in absence of curtailment, that is they show the amount of V-RES that is curtailed.
3. Quantification of BESS added value in each area, to identify where they could be more effectively integrated.
4. Optimized hourly dispatch of all the plants and storage systems in the area, provided in an additional .xlsx file.

3.1.1 - Western Cape

Table 3-1 reports the results on additional V-RES capacity (MW) & Export (GWh) and the net-export DCs for WC.

Scenario	PV [MW]	Wind [MW]	Export [GWh]
No BESS + No curt	353	2173	17697
BESS 2GWh+ No curt	172	2873	20269
No BESS + curt10%	2270	4892	28674
BESS 2GWh+curt10%	4057	4367	29854
BESS 3.2GWh+curt10%	4289	4372	30227

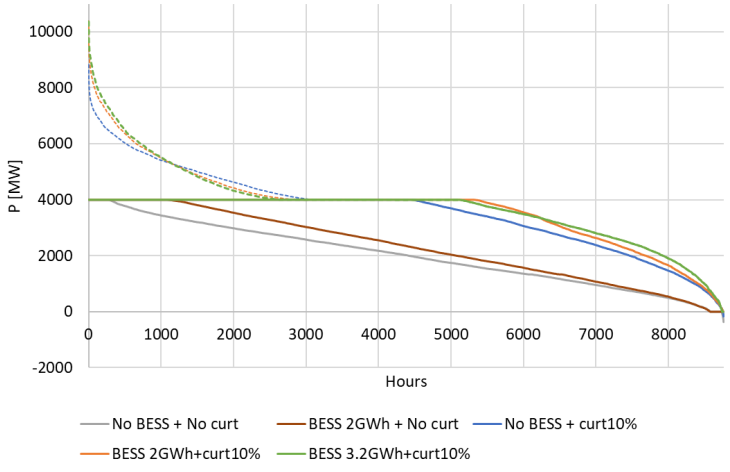


Table 3-1: Additional V-RES capacity (MW) & Export (GWh), and net-export DCs – Western Cape

From the results, the following conclusions can be derived for WC:

1. Western Cape is characterized by a good availability of wind resource, that motivates the prevalence of new wind over PV installations, which are almost negligible in the scenario without BESS and curtailment.
2. The practice of 10% curtailment does bring the largest system benefits in terms of additional capacity to install and the consequent maximization of the exports.
3. New BESS without curtailment allow to increase of around 700MW the new wind capacity at the expense of 200MW of PV, for a total increase of installed capacity of around 500MW, comparable to the size of BESS itself. This could be explained by the higher capacity factor of wind, that makes it the preferrable candidate source, and by the ability of BESS to store the excess wind energy during the night hours, when the load level is low, thus releasing the constraints occurring in the *No BESS + No curt* scenario. Regarding the curtailment cases, it is the curtailment practice that pushes the wind capacity to its limits and shaves its peaks, while BESS are used therefore to integrate additional PV, which, however, do not lead to a relevant increase of the total exported energy.
4. Notably, there are very few hours where the endogenous power goes below to zero, meaning very few hours when WC needs to import power from neighbouring areas.
5. When properly optimized, the dispatching on WC would make the province an important net exporter. Since the City of Cape Town is also expecting to install new gas turbines for mitigating load shedding, it is important to note that these turbines shall be operated when the grid is not congested, otherwise is further penalizes the maximization of the export from V-RES.
6. The above considerations suggests also that the national rotating load shedding scheme should be revised in terms of *where* and *when*. In particular, it must be avoided to implement load shedding in WC in the hours of saturation of the NTC, because this does penalize considerably the maximization of the export.
7. The above results have been reached by optimizing the dispatching of Palmiet pump storage in order to maximize the export for V-RES, subject to the technical constraints indicated by Eskom on the reservoir. The resulted operational profile differs from the current dispatching practice by Eskom. This leads to two interesting considerations:
    a. With the increasing penetration of V-RES, also the dispatching of Palmiet has to adjust accordingly, in order to sustain the maximization of V-RES.
    b. The current dispatching of Palmiet considers the pumping mode during the night hours. This is for flexibility purposes to keep some load necessary to keep the coal power plants in the north-east side of the country in operation at their minimum load. This suggests that the transition towards a deep decarbonized system in South Africa must carefully consider flexibility issues in case of change in the dispatching of the synchronous machines.

3.1.2 - Eastern Cape

Table 3-2 reports the results on additional V-RES capacity (MW) & Export (GWh) and the net-export DCs for WC. Given the abundance of wind resource and low interest for PV in the area, only wind is simulated as candidate additional capacity.

Scenario	PV [MW]	Wind [MW]	Export [GWh]
No BESS + No curt	-	1488	10048
BESS 2GWh+ No curt	-	1870	11377
No BESS + curt10%	-	3798	16276
BESS 2GWh+curt10%	-	4004	16903
BESS 3.2GWh+curt10%	-	4106	17233

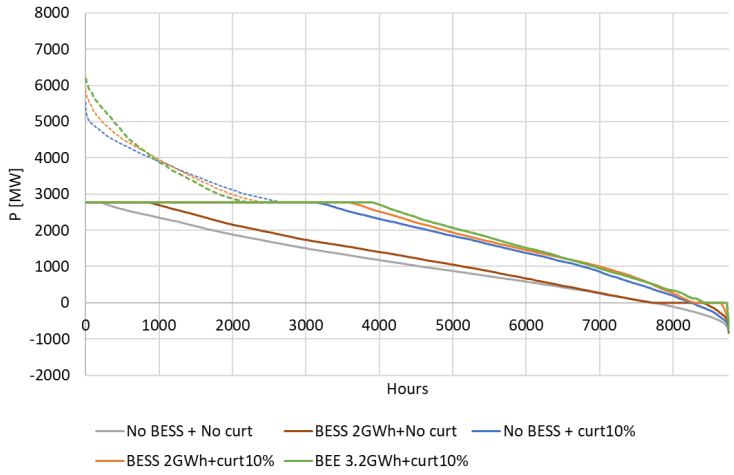


Table 3-2: Additional V-RES capacity (MW) & Export (GWh), and net-export DCs – Eastern Cape

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From the results, the following conclusions can be derived for EC:

1. Eastern Cape is characterized by an outstanding availability of wind resource, whose additional installation and generation increase significantly in the curtailment scenario.
2. The practice of 10% curtailment does bring the largest system benefits in terms of additional capacity to install and the consequent maximization of the exports.
3. The value added from BESS is almost null, as per justification indicated above for EC.
4. In all the scenarios there are a not-negligible number of hours where the endogenous power goes below to zero in all the scenarios, that is when EC needs to import power from neighbouring areas.
5. As per WC, it must be avoided to implement load shedding in WC in the hours of saturation of the NTC, because this does penalize considerably the maximization of the export.

3.1.3 - Northern Cape

Table 3-3 reports the results on additional V-RES capacity (MW) & Export (GWh) and the net-export DCs for WC. Two cases are simulated:

1. PV and Wind.
2. Only PV.

	PV and wind			Only PV		
Scenario	**PV [MW]**	**Wind [MW]**	**Export [GWh]**	**PV [MW]**	**Wind [MW]**	**Export [GWh]**
No BESS + No curt	0	78	5942	71	-	5895
BESS 2GWh+ No curt	0	584	7277	577	-	6580
No BESS + curt10%	0	3286	15726	1988	-	9223
BESS 2GWh+curt10%	0	3608	16623	2452	-	9666
BESS 3.2GWh+-curt10%	0	3750	17031	2721	-	10008

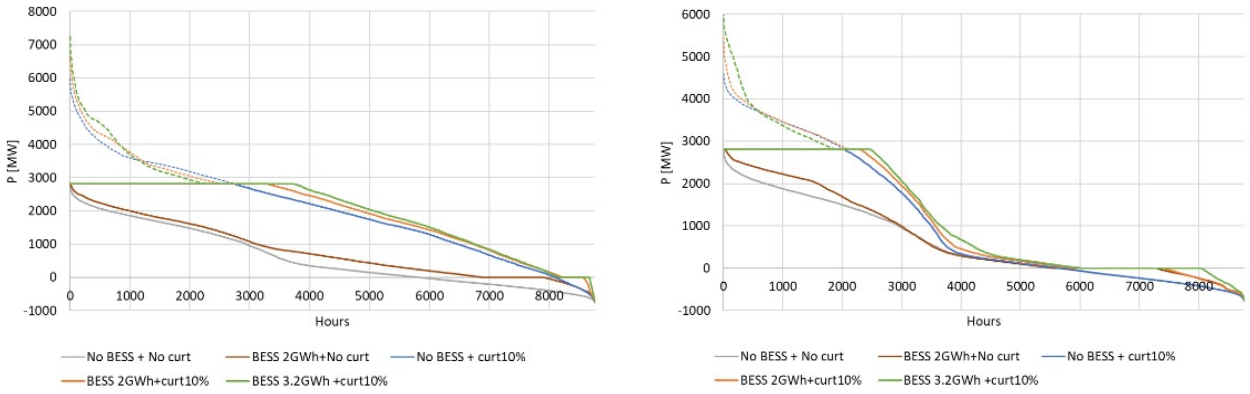


Table 3-3: Additional V-RES capacity (MW) & Export (GWh), and net-export DCs – Northern Cape

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From the results, the following conclusions can be derived for NC:

1. With neither curtailment nor BESS, the additional capacity of wind and PV is almost null, reflecting the current congested status of NC network. In fact, this is mainly attributable to the current installed PV capacity, which is already saturating the NTC during the central hours of the day. This is confirmed by the fact that the optimizer is forced to relax the no curtailment constraint to find feasible solutions for the base scenario (*no curt + no BESS*).
2. The curtailment is much more beneficial to add wind capacity than new PV. In fact, PV is congesting the network of WC during the central hours of the days at the same time and similarly in the whole WC area (i.e., coincidence factor ~ 1, meaning that all the PV are peaking at the same time all together), therefore, curtailing PV does not allow to substantially increase the installable capacity. On the contrary, wind ratings show coincidence factors < 1 on average, meaning that wind farms spread on a large territory are rarely peaking all together, enhancing the benefits of the curtailment concentrated in few hours of the years.
3. In the *wind + PV scenario*, the addition of BESS in the simulations is used for peak shaving on the existing PV and for planning only new wind capacity, while for the *only PV scenario*, BESS does contribute marginally to increase the additional capacity.
4. The latter consideration on the *only PV scenario* suggests also the following: IPPs that plan to install additional new PV capacity in the NC area should consider installing mainly hybrid PV + BESS plant to deal with network congestions in the area.

Given the peculiarity of Northern Cape, where the available capacity for new installations is limited, additional stochastic optimizations have been performed on *BESS 2GWh+curt10%* scenario to improve the reliability of the results. The settings are:

- *METHOD*: 2-stages stochastic programming.
- *INPUTS*: 10 profiles tested: 5 years profiles for PV and wind resources (2009-2023) combined with 2 years of CSP production (2021-2022)
- *OPTIMIZATION*: the profiles are tested simultaneously to find the optimal new V-RES installations that:
  - Satisfy the constraints in each condition
  - Globally maximize the export

Table 3-4 reports the results for the stochastic optimization, suggesting that the stochasticity in the profiles does not bring substantial differences with respect to the deterministic simulations.

	PV and wind			Only PV		
Scenario	**PV [MW]**	**Wind [MW]**	**Export [GWh]**	**PV [MW]**	**Wind [MW]**	**Export [GWh]**
BESS 2GWh+curt10%	0	3531	16011	2383	-	9379

Table 3-4: Additional V-RES capacity (MW) & Export (GWh), and net-export DCs – Northern Cape

3.1.4 - Hydra Cluster

Table 3-5 reports the results on additional V-RES capacity (MW) & Export (GWh) and the net-export DCs for WC. Two cases are simulated:

1. ESKOM hydro profile.
2. Optimized hydro profile.

	PV and wind			Only PV		
Scenario	**PV [MW]**	**Wind [MW]**	**Export [GWh]**	**PV [MW]**	**Wind [MW]**	**Export [GWh]**
No BESS + No curt	0	1152	10387	0	1712	13073
BESS 2GWh+ No curt	0	1515	12019	0	2075	14700
No BESS + curt10%	170	2935	17020	1724	2601	19192
BESS 2GWh+curt10%	1845	2535	18920	2046	2692	20161
BESS 3.2GWh+curt10%	2034	2549	19358	2251	2710	20624

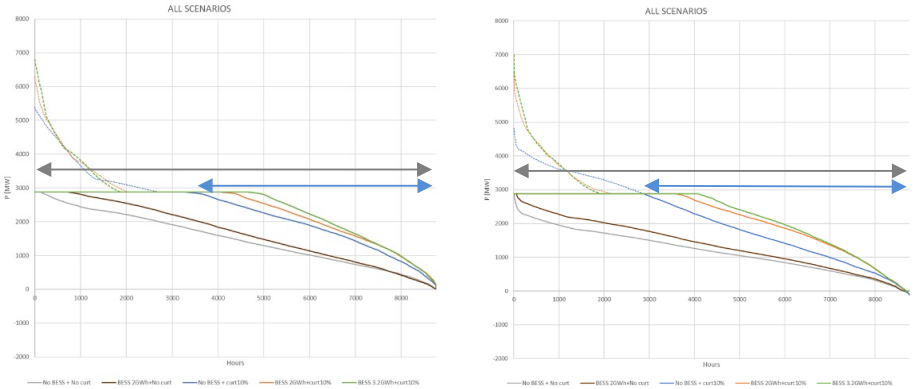


Table 3-5: Additional V-RES capacity (MW) & Export (GWh) – Northern Cape

From the results, the following conclusions can be derived for HC:

1. From the DCs, it clearly emerges that the maximisation of the exports obtained with the curtailment is more than doubling the time period when the grid is utilized at its maximum (i.e., the grey arrow is more than twice the length of the blue arrow), meaning that the time period available for any refurbishment on the grid assets is half. And, since the time period where the grid usage is maximised is likely to be during the daily hours (when PV is on), this will require to consider revising the current operational planning practices and considering maintenance during the night hours.
2. The solution with the optimized dispatching of the hydro plants allows to increase the penetration of V-RES, suggesting considering revising the current operational dispatching of Gariep and Vanderkloof plants, if compatible with the existing water-release constraints.
3. Apart from 1 scenario (the base *No BESS + No curt* in the *ESKOM hydro profile case*), the additional capacity exceeds the current expected maximum available capacity of the total S/Ss (=1.3 GW, net of the planned *"new" Hydra D, Hydra B, and Gamma*).

3.1.5 - BESS analysis

The BESS analysis consists of the evaluation of the value of the V-RES energy accumulated by the BESS that otherwise would be lost. It is calculated as the additional export and local load supply achievable with the BESS, with respect to the no-BESS case. This is valorised at an average LCOE of 33 USD/MWh for South African V-RES, derived by the previous *Integration of Non-Programmable Renewable Energy in the National Electric System of South Africa study* by CESI. It is then divided by the estimated yearly CAPEX for the BESS installation, set equal to 369 USD/kWh[15] divided by the BESS lifetime. The obtained ratio provides an economic indicator of value added delivered by BESS: a value < 1 means that BESS alone cost more than the whole additional V-RES value, while a value > 1 means that the whole additional V-RES value overcomes the BESS investment and operating costs.

Results are reported in Table 3-6.

[15] *Source: Utility-Scale Battery Storage | Electricity | 2022 | ATB | NREL*
Lifetime of the battery: 20 Years https://www.lazard.com/media/42dnsswd/lazards-levelized-cost-of-storage-version-70-vf.pdf

		V-RES Yearly Value (M$)	BESS Yearly Cost (M$)	V-RES Value/Yearly Battery Cost [-]
WC	2 GWh	38.96	36.90	**1.06**
	3.2 GWh	51.25	59.04	**0.87**
	2 GWh no curt	85.03	36.90	**2.30**
EC	2 GWh	24.00	36.90	**0.65**
	3.2 GWh	35.40	59.04	**0.60**
	2 GWh no curt	51.11	36.90	**1.39**
NC	2 GWh	33.73	36.90	**0.91**
	3.2 GWh	48.30	59.04	**0.82**
	2 GWh no curt	64.10	36.90	**1.74**
	2 GWh only PV	30.56	36.90	**0.83**
	3.2 GWh only PV	47.72	59.04	**0.81**
	2 GWh only PV no curt	38.66	36.90	**1.05**
HC	2 GWh hydro profile	62.82	36.90	**1.70**
	3.2 GWh hydro profile	77.28	59.04	**1.31**
	2 GWh hydro profile no curt	54.04	36.90	**1.46**
	2 GWh hydro opt	31.98	36.90	**0.87**
	3.2 GWh hydro opt	47.25	59.04	**0.80**
		53.68	36.90	**1.45**

Table 3-6: BESS valorisation in the different supply areas

Table 3-7 reports the figures on the yearly energy discharged and the number of cycles faced by the BESS for one year, which are meant to provide an indication of the usability of the BESS in the different areas and in the different scenarios.

	BESS 2GWh+ No curt		BESS 2GWh+curt10%		BESS 3.2GWh+curt10%	
	Yearly Energy (GWh)	Cycles	Yearly Energy (GWh)	Cycles	Yearly Energy (GWh)	Cycles
EC	233	124	831	442	1284	427
WC	137	73	987	525	1581	526
NC	284	151	848	451	1289	428
$NC_{only\ PV}$	484	257	715	380	1240	412
$HC_{hydro\ profiles}$	10	5	745	396	1153	383
$HC_{hydro\ opt}$	51	27	747	397	1145	381

Table 3-7: BESS discharged energy and cycles. The cycles of the BESS are meant as equivalent full cycles and computed as the ratio of yearly energy throughput (kWh) to the usable capacity (kWh)[16] .

[16] *Ralon, Pablo, et al. «Electricity storage and renewables: Costs and markets to 2030.» International Renewable Energy Agency: Abu Dhabi, United Arab Emirates 164 (2017).*

Finally, next Table 3-8 reports the additional capacity installed in the different scenarios compared to the *No BESS + No curt* scenario in all the areas.

	BESS 2GWh+No curt	No BESS+curt10%	BESS 2GWh+curt10%	BESS 3.2GWh+curt10%
	Add. V-RES [% / MW]	Add. V-RES [% / MW]	Add. V-RES [% / MW]	Add. V-RES [% / MW]
EC	126% / +382 MW	255% / +2310 MW	269% / +2516 MW	1434% / +2618 MW
WC	121% / +519 MW	284% / +4636 MW	334% / +5898 MW	1370% / +6135 MW
NC	753% / +506 MW	4213% / +3208 MW	4626% / +3530 MW	26815% / +3672 MW
$NC_{only\ PV}$	812% / +506 MW	2800% / +1917 MW	3454% / +2381 MW	14076% / +2650 MW
$HC_{hydro\ profiles}$	132% / +363 MW	270% / +1953 MW	380% / +3026 MW	1902% / +3443 MW
$HC_{hydro\ opt}$	121% / +363 MW	253% / +2613 MW	277% / +3208 MW	1363% / +3249 MW

Table 3-8: Additional V-RES allowed by BESS and curtailment

The following conclusions can be drawn:

1. The result of the analysis shows that in a deeply constrained situation – as present in South Africa – where the curtailment practice is not allowed, the introduction of BESS allows to integrate more V-RES, whose additional production allow to off-set the cost of BESS itself (i.e., ratios > 1). This is especially evident in Western Cape, followed by Northern Cape, Hydra Cluster, and then Eastern Cape.
2. In terms of relative additional V-RES unlocked by BESS, NC is the area where BESS provide the largest benefits.
3. In terms of absolute additional V-RES unlocked by BESS, in the no-curtailment scenario, all the areas are characterised by similar results, that is an increase of additional capacity of around 500 MW, on average. In the 10%-curtailment scenarios, WC, and HC (with static hydro profile) are the areas where BESS allow to unlock around 1200 MW of new V-RES with respect to the 10%-curtailment only case, while NC experiences around 300-400 MW of additions.
4. The above results should be read in the light of the benefits provided by BESS with respect to the 10%-curtailment case. In all the cases, the 10%-curtailment practice allows to reach the largest benefits (both in terms of new V-RES capacity and additional export) with respect to the only-BESS case, and at lower expected costs. Overall system costs for BESS deployment are in fact expected to be much higher that the impact of 10%-curtailment on the cost of the electricity service.
5. Without curtailment, the n° of cycles are very low, suggesting that BESS is mainly used for peak shaving in all the regions apart from NC with only PV. The extreme case is HC, where the yearly N° of cycles is around 5: in fact, from the dispatching profiles, it emerges indeed that BESS is mainly utilized at the beginning of the year, to shave the highest production of hydro plants. BESS with higher power-to-energy ratio (e.g., 2hr-BESS) may be more appropriate to be tested than the 4hr-BESS to deal with peak shaving.
6. With curtailment, BESS is definitely valorised also as daily energy storage, with more than 1-cycle per day. WC is the area where BESS is utilized the most, immediately followed by NC. Also, the ratio between V-RES value / BESS cost is in favour of HC, followed by WC, NC, and finally EC.

The considerations above suggest that, from a pure energy perspective, the results do not indicate one area as significantly more suitable than others for the installation of BESS. Therefore, in terms of future BESS installations, the following recommendations are indicated:

1. The areas with no carrying capacity available and the areas with system balancing and ROCOF issues should be prioritized.
2. Where there are less balancing/inertia problems and available supply area capacity, the curtailment outperforms the BESS advantages in terms of increasing V-RES penetration.

All the above outcomes shall be considered in light of the fact that we only tested a limited size of BESS that was compatible with the target year (i.e., 2025). Therefore, the above results and conclusions on the BESS analysis must not be used to infer on the BESS advantages/disadvantages in the long run, which is out of the scope of the analysis.

3.2 - Interconnected Model – GCCA 2025

For the interconnected model, the following outcomes are reported:

1. Additional Capacity [MW] of PV and wind that can be potentially installed in 2025, for each simulated scenario and for each supply area.
2. As in the *Standalone Supply Areas* simulations, the net-export Duration Curves (DCs) of the resulting optimal dispatch in each scenario are studied. In this case, the curve shows the hourly next export values, that is the total production in the area plus the import from the different lines minus the total load consumption, sorted in descending order. The advantage in the use of a DC-kind representation is that it provides an overall overview on how many hours the energy production saturates the NTC, giving a representation of the effectiveness of V-RES integration in the area. The dashed curves show the theoretical maximum export in case the V-RES plants were not curtailed, thus indicating the case with unconstrained network.
3. Results are shown with and without additional BESS capacity in FS and NW.
4. An assessment of the saturation levels of the different corridors is performed, to identify the most congested interconnectors and suggest a prioritization of the planned reinforcements.
5. An overall analysis that focuses on the curtailment is reported to highlight and give evidence of the system benefits of the curtailment practice.

3.2.1 - Western Cape

Table 3-9 reports the results of additional V-RES capacity (MW) & Export (GWh) and the net-export DCs for WC. The two scenarios are reported.

Base case				Base + BESS in NW and FS			
PV [MW]	Wind [MW]	Export [GWh]	Import [GWh]	PV [MW]	Wind [MW]	Export [GWh]	Import [GWh]
0	2031	14012	755	0	2056	14132	766

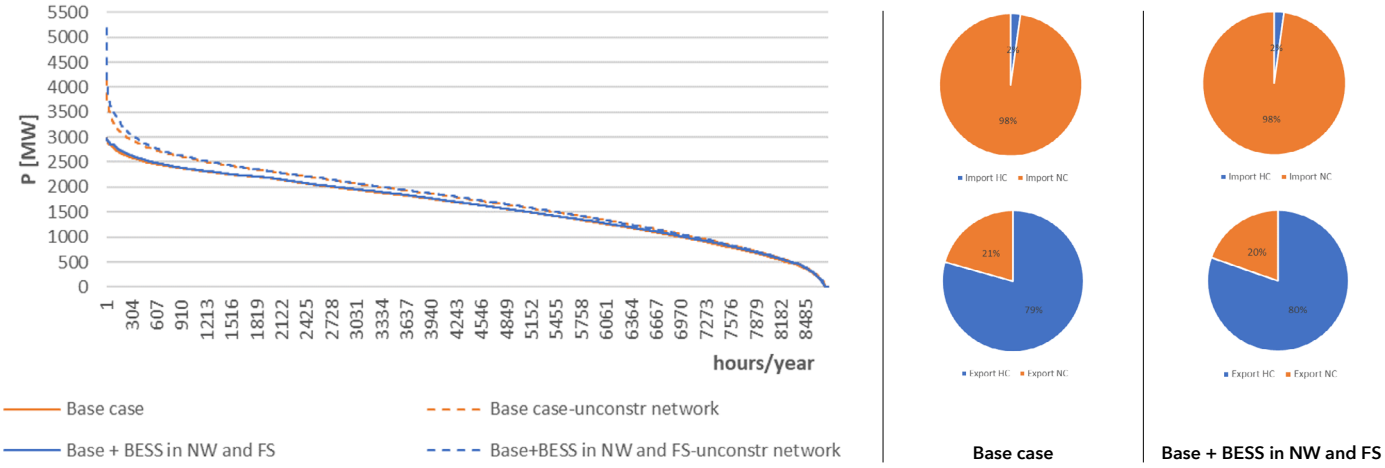


Table 3-9. Additional V-RES capacity (MW) & Export (GWh), and net-export DCs interconnected model– Western Cape

From the results, the following conclusions can be derived for Western Cape:

1. By incorporating rooftop PV capacity and interconnecting different areas, the optimal installed PV capacity approaches zero. Conversely, due to a more abundant wind resource, it becomes feasible to install 2031 MW (2056 MW in the BESS scenario) of wind. This enables meeting the local energy demand while also exporting a portion of the generated power.
2. Examining the DCs, differently from the *Standalone Supply Area* case, the load is met throughout all 8760 hours of the year also thanks to the imports from Northern Cape and Hydra Cluster. For the majority of these hours, the region has the capacity to export power to other regions.
3. In both scenarios, the imported flux in the region is minor and it comes from Northern Cape for 98%, with a negligible fraction from Hydra Cluster. On the other hand, the region is mainly exporting to Hydra Cluster.
4. The NTC is never saturated, suggesting that the export capacity from WC is not limited by its NTC, but from the constraints in the neighbouring areas, especially HC (see section 3.2.8).
5. BESS in FS and NW do not significantly release constraints for installing new additional V-RES capacity in WC.

3.2.2 - Eastern Cape

Table 3-10 reports the results of additional V-RES capacity (MW) & Export (GWh) and the net-export DCs for EC. The two scenarios are reported.

Base case				Base + BESS in NW and FS			
PV [MW]	Wind [MW]	Export [GWh]	Import [GWh]	PV [MW]	Wind [MW]	Export [GWh]	Import [GWh]
0	1011	7870	4452	0	1028	7846	4414

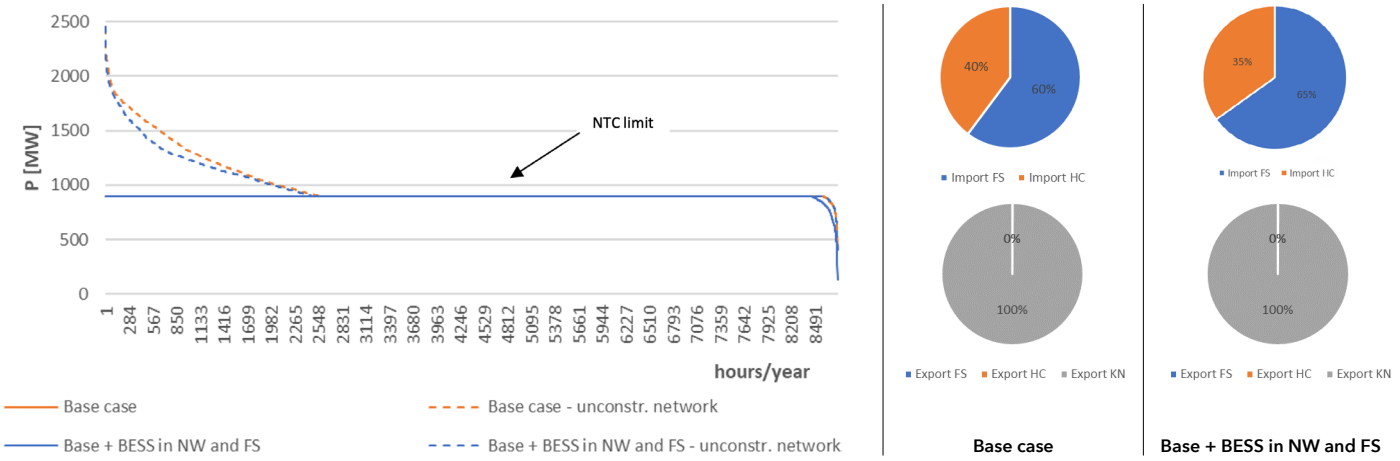


Table 3-10. Additional V-RES capacity (MW) & Export (GWh), and net-export DCs interconnected model– Eastern Cape

From the results, the following conclusions can be derived for Eastern Cape:

1. From DCs, it is evident that the low NTC of EC considerably constraints the export from the area, and therefore the installable wind capacity. Indeed, the load of the area is always satisfied but also the export is saturating the NTC for almost all the hours of the year.
2. The region is totally exporting to the outer region of KN and importing a 60% of the total from Free State. The remaining comes from HC.
3. BESS in FS and NW do not significantly impact the new additional V-RES capacity in EC.

3.2.3 - Northern Cape

Table 3-11 reports the results of the additional V-RES capacity (MW) & Export (GWh) and the net-export DCs for NC. The two scenarios are reported.

Base case				Base + BESS in NW and FS			
PV [MW]	Wind [MW]	Export [GWh]	Import [GWh]	PV [MW]	Wind [MW]	Export [GWh]	Import [GWh]
0	1011	7870	4452	0	1028	7846	4414

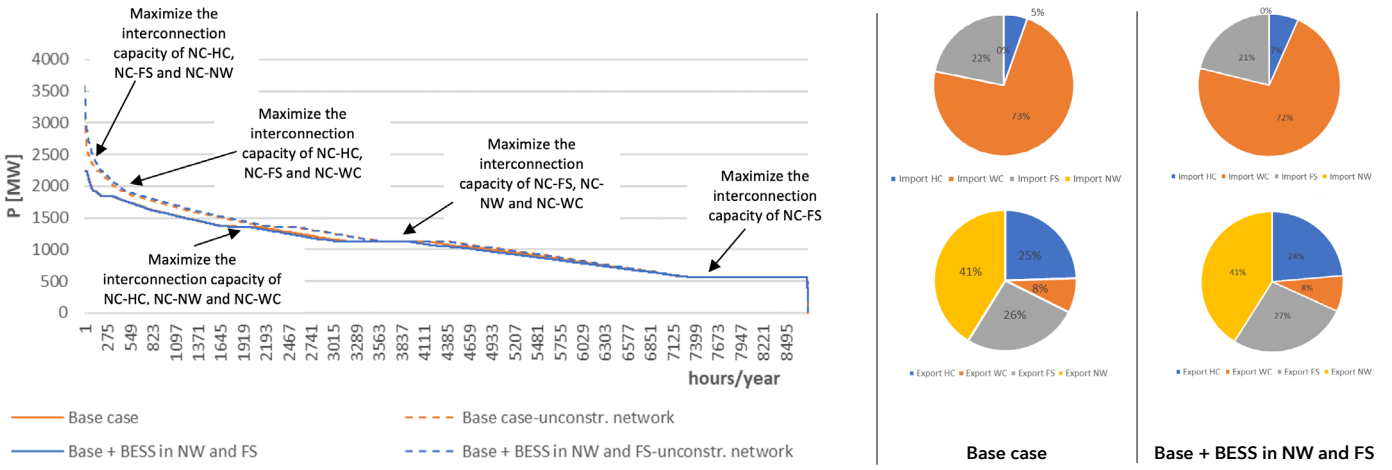


Table 3-11. Additional V-RES capacity (MW) & Export (GWh), and net-export DCs interconnected model– Northern Cape

From the results, the following conclusions can be derived for Northern Cape:

1. Even with the interconnections between areas, the additional V-RES capacity remains minimal, due to the limited hosting capacity of the NC network. Only a modest amount of wind capacity, approximately 338 MW (343 MW in the BESS scenario), can be integrated in the region. This limitation is largely attributable to the existing PV capacity, which saturates the NTC during peak daylight hours, and also to the congestion in the interconnections with FS and NW, which are loaded for most of the time (see section 3.2.9).
2. Since all the connected areas are almost saturated, the NTC of NC remains underutilized for almost the entire year.
3. The different plateaus of the curve represent the moment of maximization of the export capabilities on the different corridors. For example, the plateau around 1130 MW refers to the net export used to maximize the export of FS, NW, and WC connections.
4. The region imports mainly from Western Cape, followed by FS and HC. The interconnection line with North West is only used for export. At the same time, the region exports also to FS, HC and a 8% to WC.
5. BESS in FS and NW do not significantly impact the new additional V-RES capacity in NC.

3.2.4 - Hydra Cluster

Table 3-12 reports the results of the additional V-RES capacity (MW) & Export (GWh) and the net-export DCs for HC. The two scenarios are reported.

Base case				Base + BESS in NW and FS			
PV [MW]	Wind [MW]	Export [GWh]	Import [GWh]	PV [MW]	Wind [MW]	Export [GWh]	Import [GWh]
0	0	19877	15103	0	0	19957	15183

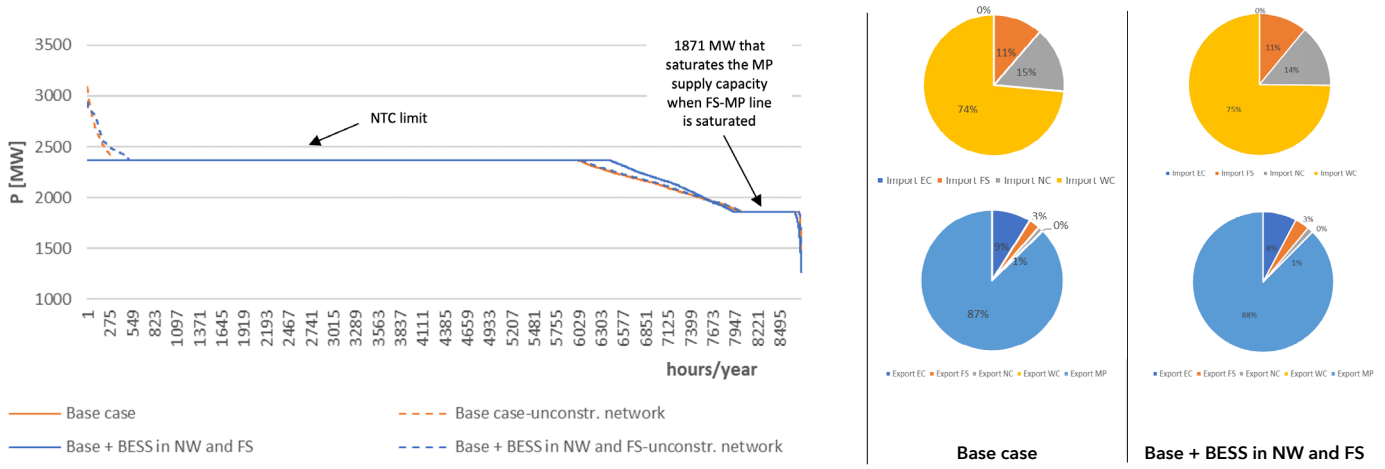


Table 3-12. Additional V-RES capacity (MW) & Export (GWh), and net-export DCs interconnected model – Hydra Cluster

From the results, the following conclusions can be derived for Hydra Cluster:

1. No additional PV and wind capacity is expected in the region, which is coherent with HC nature of transit area.
2. HC is the supply area with the highest yearly exported energy (close to 20 TWh). The export capability saturates the NTC for more than 6000 hours per year. The area is exporting more than 17 TWh to MP and importing from the other areas such as NC, WC, and FS. The lower plateau represents the 1871 MW that saturates the supply capacity of MP when the corridor FS-MP is already exporting at its maximum interconnection capacity.
3. BESS in FS and NW do not significantly impact the new additional V-RES capacity in NC, but they slightly benefit the export with an increase of 80 GWh/year.

3.2.5 - Free State

Table 3-13 the results of the additional V-RES capacity (MW) & Export (GWh) and the net-export DCs for FS. The two scenarios are reported.

Base case				Base + BESS in NW and FS			
PV [MW]	Wind [MW]	Export [GWh]	Import [GWh]	PV [MW]	Wind [MW]	Export [GWh]	Import [GWh]
938	0	16946	2898	1325	0	16893	3153

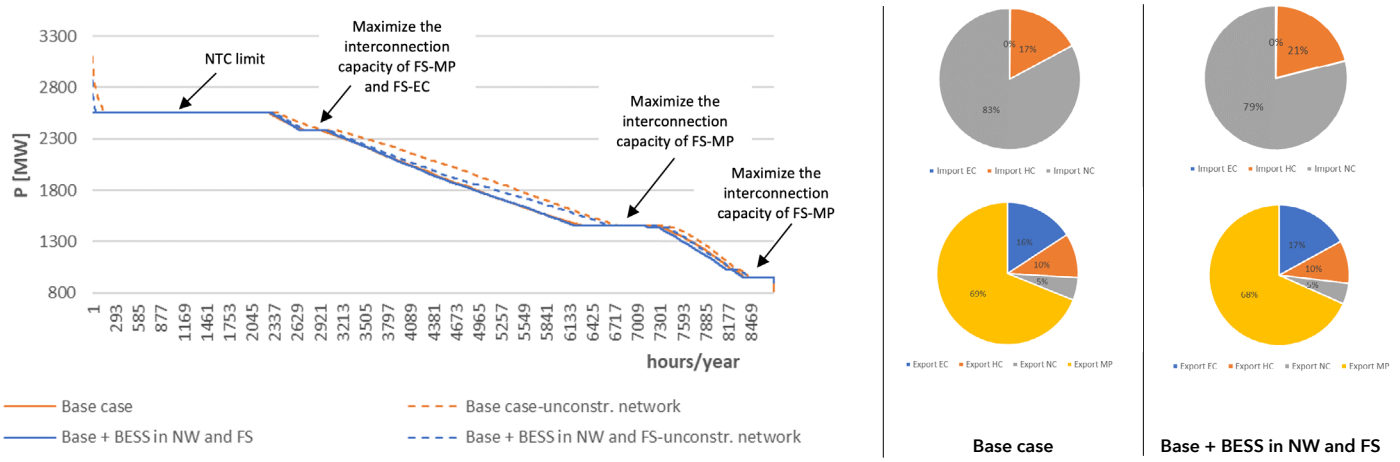


Table 3-13. Additional V-RES capacity (MW) & Export (GWh), and net-export DCs interconnected model – Free State

From the results, the following conclusions can be derived for FS:

1. Given the limited wind resource in this region, the only candidate V-RES is the PV, with optimal additional PV capacity reaching 938 MW (1325 MW in the BESS scenario).
2. The incorporation of BESS in FS and NW facilitates a substantial increment in the potential for PV installations, resulting in an increase of 387 MW (40%) of new capacity. This observation is in line with the expectations, as the deployment of batteries exerts a direct influence in the area where they are installed, leading to an enhanced utilization of solar resources.
3. On the other hand, the LDCs in both scenarios exhibit noteworthy similarities. This suggests that BESS in FS is primarily used to increase the installable PV capacity and slightly increase the import from EC, HC, and NT to finally meet the internal load only and reduce significantly the generation from coal power plant, which reduces from 15045 to 14039 GWh.
4. The export is almost 17000 GWh/year, and it is mainly directed to the external region of MP. Almost 7000 GWh/year of export comes from the coal-based production[17]. Coal is used in much prevalence during the night hours. This indicates that during the light hours, the supply capacity of MP is almost fully satisfied from importing V-RES production, which hence limits the possibility to install additional PV production in the FS region. The import is mainly from NC, followed by HC. An almost negligible flux is imported from EC, due to the NTC constraints.

[17] *FS is exporting coal-based production also towards MP since the objective function is the maximisation of the export through the Eastern regions.*

3.2.6 - North West

Table 3-14 reports the results of the additional V-RES capacity (MW) & Export (GWh) and the net-export DCs for NW. The two scenarios are reported.

Base case				Base + BESS in NW and FS			
PV [MW]	Wind [MW]	Export [GWh]	Import [GWh]	PV [MW]	Wind [MW]	Export [GWh]	Import [GWh]
5864	0	7601	10809	6436	0	7731	9929

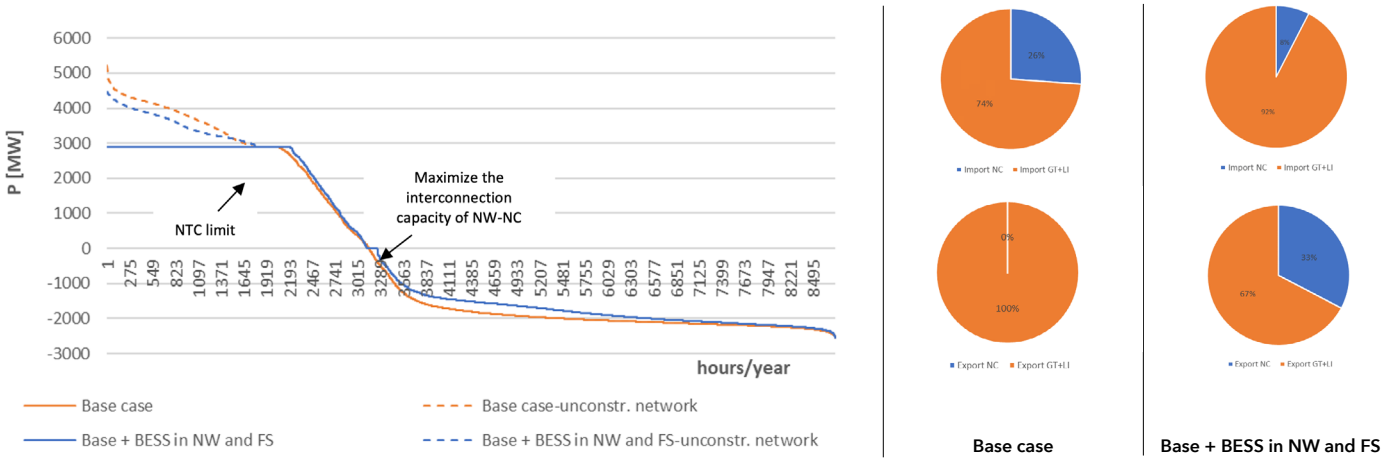


Table 3-14. Additional V-RES capacity (MW) & Export (GWh), and net-export DCs interconnected model– North West

From the results, the following conclusions can be derived for NW:

1. NW is a net importing supply area from GT and LI, as represented in Table 3 14 above, where the power becomes negative for almost two-thirds of the year. This is coherent with the fact that the only endogenous generation fleet in NW and the imports from NC are composed by solar production.
2. As seen for FS, given the limited wind resource in this region, the only candidate V-RES in the area is PV, whose optimized additional capacity reaching approximately 5864 MW (6436 MW in the BESS scenario).
3. The incorporation of BESS facilitates a substantial increment in the potential for PV installations, resulting in an increase of 572 MW (around 10%).
4. The export capacity is more than 7600 GWh/year in both scenarios, and it is mainly directed towards the external region of GT and LI. The BESS addition also introduces the possibility for the region to export a much higher flux towards Northern Cape, while the import from the same region reduces.
5. Also in this case, the LDCs exhibit notable similarities between the cases with and without BESS. As per FS, this suggests that BESS in NW is not directly beneficial to increase the export towards the East side of the country, but it is primarily used to increase the installable PV to finally meet the internal load only and reduce significantly the import from GT+LI (which is mainly coal-based), which reduces from 10809 to 9929 GWh. Also, it allows to export excess power to NC.

3.2.7 - External regions

Table 3-15 reports the DCs of the exports to the external regions of MP, KN, LI and GT.

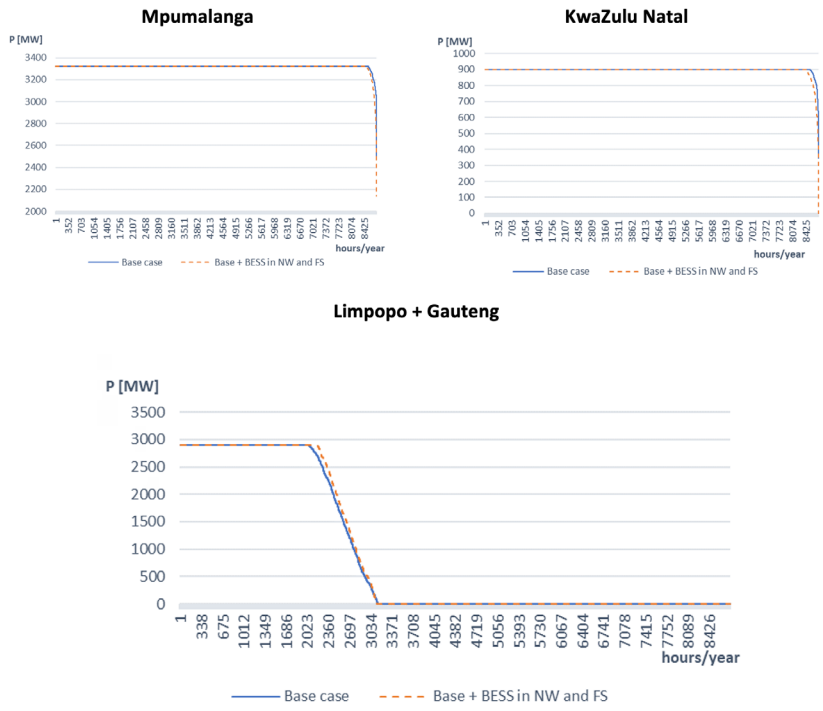


Table 3-15. Export into the external regions MP, KN, LI, and GT

From the results, the following conclusions can be derived for the external regions:

1. MP is connected to FS and HC, and its maximum import capacity (3320 MW) is saturated almost all the hours of the year. During the light hours, the saturation is by far attributable to the V-RES production. This suggests the following two conclusions:
    a. MP is the supply area where the great majority of the V-RES production coming from the West-side of the Country converges and is then redistributed towards the East-side of the Country.
    b. The capacity freed-up by the expected decommissioning of coal power plants in MP would serve to increase the production and evacuation of more V-RES import, especially the PV production during the day. This reduces the room and interest for a direct replacement of the coal plants with local PV installations in MP, while wind may be a more interesting option to investigate.
2. KN is connected only to EC, and its import is largely constrained by the NTC of EC, that is 900 MW, suggesting that interventions aimed at reinforcing the internal network in EC are expected to free-up large room for additional V-RES installations in the West side of the country.
3. LI and GT are both connected only to NW, and they are considered as a single zone in the results. In this case, the export towards GT+LI is limited by the NTC of NW for almost one-third of the year, which reflects the fact that the corridor is only used to evacuate the extra PV generation from NW, since the import in NW from NC regions is only used to satisfy the internal NW load.
4. The DCs in the different external areas for the two w/ and w/o scenarios are similar, for the same considerations introduced before for NW and FS, that is: BESS in FS and NW are useful predominantly to contribute to satisfy the internal load and reducing the coal generation (directly in FS and indirectly in NW from the import from LI and GT).

Total exports to MP+KN+GT+LI (GWh)			
	MP	KN	GT+LI
Base case	29059	7865	7601
Base case + BESS in FS and NW	29033	7837	7730

Table 3-16. Total import w and w/o BESS in FS and NW

3.2.8 - Curtailment vs no-Curtailment considerations

This section reports a resuming quantitative analysis of the potential system benefits that a 10%-curtailment may introduce to facilitate the penetration of V-RES in the South African energy system.

An additional simulation is performed for both the scenarios with and without BESS in NW and FS, while constraining the model to exclude the curtailment practice[18].

The results are reported in terms of differences (Δ) of additional V-RES capacity (Table 3 17) and the overall [GWh] energy generated by new and existing V-RES (Table 3 18) between the case with and without the 10%-curtailment practice.

The following conclusions can be derived:

1. On the capacity, curtailment is definitively benefitting new wind capacity, by unlocking GWs of new installations that would otherwise be unable to be connected. Without curtailment, basically no additional wind could be potentially installed in the Capes, reflecting the results of the GCCA 2025. The benefit on PV is less evident, and this is aligned with the intrinsic properties of PV production (especially if provided with tracking) that presents daily peaks that are quite flat and persistent for more than 10% of their daily production.
2. On the overall energy produced:
    a. Curtailment is definitively increasing new overall wind production, more than 50%, meaning that the overall 10%-curtailment applied to the generation peaks of existing and new installations is much more than compensated by the increased of production of the new additional capacity.
    b. Curtailment only slightly improves the overall solar production of existing and new PV plants [+1.1 TWh / + 0.5 TWh], especially with the BESS in NW and FS. Again, this result is coherent with the intrinsic properties of PV production (especially if provided with tracking) that does not fit well with the 10%-curtailment proposal.
    c. Globally, the 10%-curtailment practice is increasing by around 25% the production from V-RES, off-setting by far the 10%-lack of production introduced during the curtailment hours.

[18] *1%-curtailment was kept in order to avoid infeasibilities of the model.*

		Base case			Base case + BESS in NW and FS		
		w/ 10% curtailment	w/o curtailment	Δ%	w/ 10% curtailment	w/o curtailment	Δ%
NC	New PV	0	0	**0**	0	0	**0**
	New wind	337	0	**curtailment unlocks capacity**	343	0	**curtailment unlocks capacity**
WC	New PV	0	0	**0**	0	0	**0**
	New wind	2022	25	**8045%**	2056	0	**curtailment unlocks capacity**
EC	New wind	1011	17	**6008%**	1028	0	**curtailment unlocks capacity**
HC	New PV	0	0	**0**	0	0	**0**
	New wind	0	0	**0**	0	0	**0**
FS	New PV	1012	659	**53.4%**	1479	1309	**13%**
NW	New PV	5864	4494	**30.5%**	6485	5126	**26.5%**
TOT	New PV	6876	5153	**33.4%**	7964	6435	**23.8%**
	New wind	3370	42	**7924%**	3427	0	**curtailment unlocks capacity**

Table 3-17. Installed capacity w/ and w/o curtailment [MW]

		Base case			Base case + BESS in NW and FS		
		w/ 10% curtailment	w/o curtailment	Δ%	w/ 10% curtailment	w/o curtailment	Δ%
TOT	PV	28051	26906	**4.3%**	30329	29866	**1.6%**
	wind	31846	21087	**51.0%**	32063	20912	**53.3%**
	TOT	59897	47993	**24.8%**	62392	50778	**22.9%**

Table 3-18. Total and relative energy produced by new and existing V-RES plants w/ and w/o curtailment [GWh]

All these considerations can translate in a number of possible outcomes at IPPs' and consumers' level:

1. When talking about curtailment, it is important to also consider the perspective of individual IPPs, since the curtailment practice, installed capacity being equal, will cause an expected *loss of earnings* of 10% for both new and existing installation[19].
2. The implementation of the curtailment practice shall consider all the obligations that ESKOM has in terms of guaranteeing of the minimum levels of network availability and the contractual arrangements with the existing IPPs.
3. Carefulness and attention should be paid to avoid discrimination between IPPs that are operating under different contract frameworks and conditions imposed by curtailment (e.g., operating IPPs vs IPPs in constructions with already-signed PPA vs future RMIPPPP).

[19] *However, on wind, this "loss" shall be read by considering also that without curtailment, very little wind capacity could be accommodated in South Africa.*

4. In general, our results show that the expected benefits achievable from the massive increase of low-cost V-RES production that can be reached by curtailment (around 20% estimated above) can be the driver to remunerate back the deemed-but-not-evacuated energy (e.g., for existing IPPs) and/or to cover the expected increase of the off-take tariff to compensate the possible losses of earnings (e.g., for new IPPs).
5. With respect to a *carpet*-curtailment to all the V-RES fleet (existing and new), it should be considered the possibility to implement a punctual 10%-curtailment to address only the most critical plants in the most critical areas and situations, that, when curtailed in some circumstances, may bring the highest overall system benefits.
6. The future PV penetration reveal concerns on the nature, in terms of utility-scale vs rooftop PV, of the future installations. This is a crucial aspect that impacts on the effective implementation of curtailment. In fact, the application of curtailment to rooftop PV is not as immediate and easily manageable as per utility-scale, and its application is questionable. Therefore, as conservative scenario, we tested a case that admits the 10%-curtailment for wind only. The results in terms of additional V-RES capacity and *overall* and *relative* energy production are reported in Table 3-19 and Table 3-20. The following conclusions can be derived:
    a. On the capacity, curtailment applied only to wind is still benefitting new wind capacity, by unlocking almost the same GWs of new installations that could be obtained by applying 10%-curtailment to both wind and PV. On the contrary, the additional PV capacity is around 2 GW lower than the case where curtailment is applied to both wind and PV, which makes it even slightly lower (-280 MW / -500 MW) than the case where curtailment is not applied at all. This is because, with the 10%-curtailment practice applied only to wind, the supply capacity of FS is mostly "absorbed" by the import of a massive increase of wind from the inner West regions, which does not fit well with the imposed rigid production (0%-curtailment) to PV.
    b. On the overall energy produced:
        i. The increase in overall wind production is close to the results obtained with the 10%-curtailment practice applied to both PV and wind (31046 GWh vs 31846 GWh in the base case / 31070 GWh vs 32063 GWh with BESS in FS and NW), remaining almost 50% higher than the no-curtailment option.
        ii. PV production decreases slightly with respect to the results obtained with the 10%-curtailment practice applied to both PV and wind (26250 GWh vs 28051GWh in the base case / 28754 GWh vs 30329 GWh with BESS in FS and NW) and becoming almost -2/-4% lower than the no-curtailment option, reflecting the reduction in the expected additional PV capacity reported above.

Results demonstrate as that the 10%-curtailment applied to wind only would allow cause a slight decrease of the systems benefits: a reduction of the exported energy of around 2600 GWh in both scenarios. This is mainly caused by the reduction in the expected additional PV capacity (-2 GW in FS) and less overall PV production (-1800 GWh / -1600 GWh). In conclusion, non-controllable rooftop PV installations, which are not expected to have major impacts on the wind installations, may reduce the need and capacity to accommodate new utility scale PV plants.

		Base case			Base case + BESS in NW and FS		
		w/ 10% curtailment (only wind)	w/o curtailment	Δ%	w/ 10% curtailment (only wind)	w/o curtailment	Δ%
NC	New PV	0	0	**0**	0	0	**0**
	New wind	316	0	**curtailment unlock capacity**	317	0	**curtailment unlock capacity**
WC	New PV	0	0	**0**		0	**0**
	New wind	1896	25	**7484%**	1900	0	**curtailment unlock capacity**
EC	New wind	948	17	**5476%**	950	0	**curtailment unlock capacity**
HC	New PV	0	0	**0**	0	0	**0**
	New wind	0	0	**0**	0	0	**0**
FS	New PV	378	659	**-43%**	828	1309	**-37%**
NW	New PV	4494	4494	**0%**	5131	5126	**0%**
TOT	New PV	4872	5153	**-5%**	5959	6435	**-7%**
	New wind	3160	42	**7424%**	3167	0	**curtailment unlock capacity**

*Table 3-19. Installed capacity w/ and w/o curtailment applied to **wind only** [MW]*

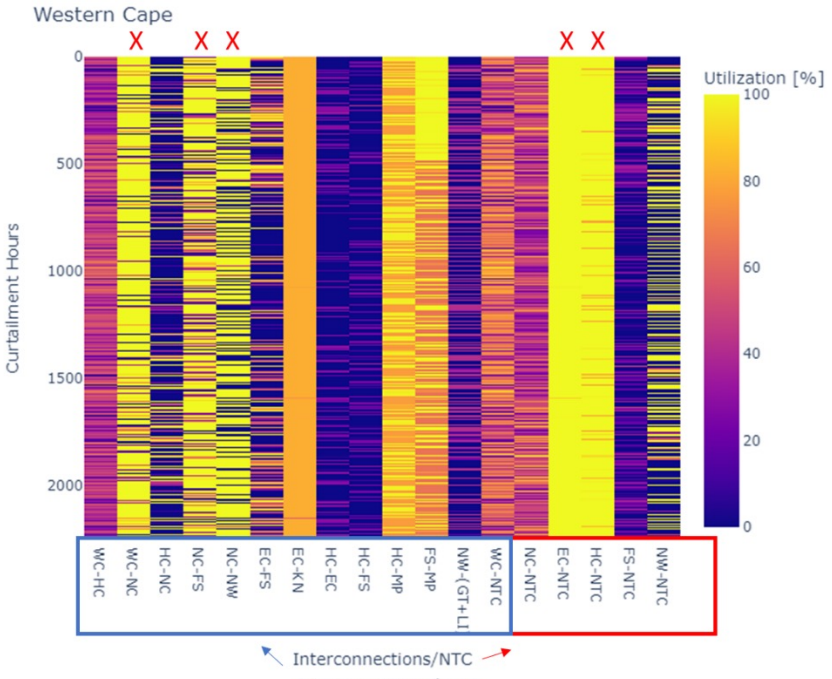
		Base case			Base case + BESS in NW and FS		
		w/ 10% curtailment (only wind)	w/o curtailment	Δ%	w/ 10% curtailment (only wind)	w/o curtailment	Δ%
TOT	PV	26250	26906	**-2.4%**	28754	29866	**-3.7%**
	wind	31046	21087	**47.2%**	31070	20912	**48.6%**
	TOT	57296	47993	**19.4%**	59824	50778	**17.8%**

*Table 3-20. Total and relative energy produced by new and existing V-RES plants w/ and w/o curtailment to **wind only** [GWh].*

3.2.9 - Analysis of the corridors and areas constraints

This section analyses the expected levels of loading on the main electric corridors and intra-areas during the V-RES curtailment periods, to inform possible network reinforcement strategies. It shall be noted that, being this analysis a purely energy optimisation, it does not reflect the actual "impedance map" of the grid that might give different results. Therefore, the purpose of the analysis is to hint at possible corridors/areas that may reveal a high degree of saturation to be studied through further network studies.

The following charts give a graphical representation of the expected load factor on the interconnections and the saturation of the NTC during the hours of curtailment for each supply area. Each row shows an instant of time (displayed chronologically) when some V-RES (either wind, PV, new or existing), are curtailed. The columns represent the interconnections and the NTC of each supply area and the colours show the percentage of utilization of the lines and NTC with respect to their maximum limit. The interconnections and NTC which are utilised more than 90% of their maximum limit for at least 60% of the curtailment hours are highlighted with red crosses.



N curt. Hours: 2248

Most loaded lines:

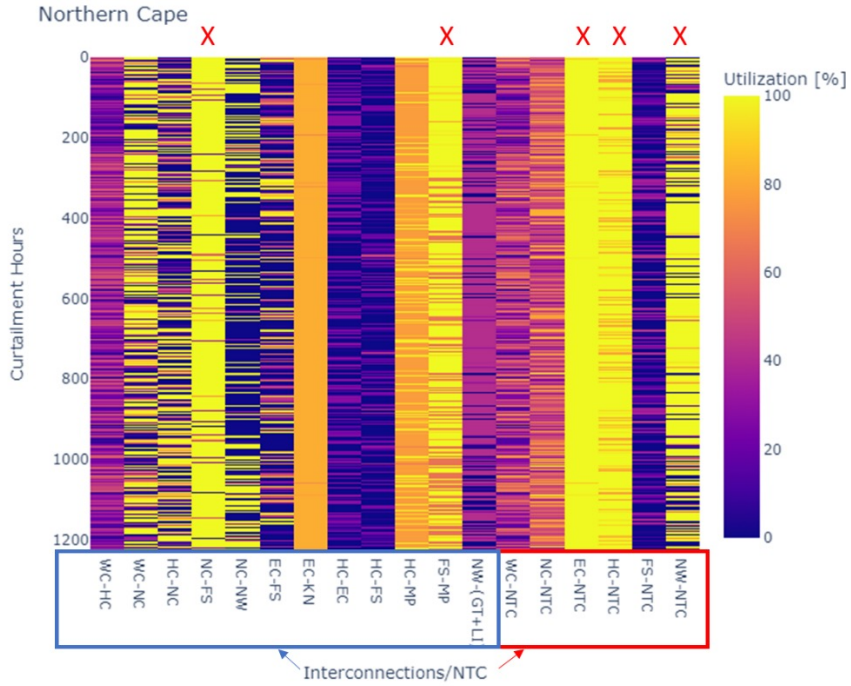
WC-NC	NC-FS	NC-NW
78%	62,5%	69%

Most saturated NTC:

EC	HC
99,5%	93%

The NTC in WC is never exploited at its maximum limit.

The curtailment is triggered by saturations occurring downstream, particularly on the interconnections with NC, and the limited NTC of EC and HC.



N curt. Hours: 1226

Most loaded lines:

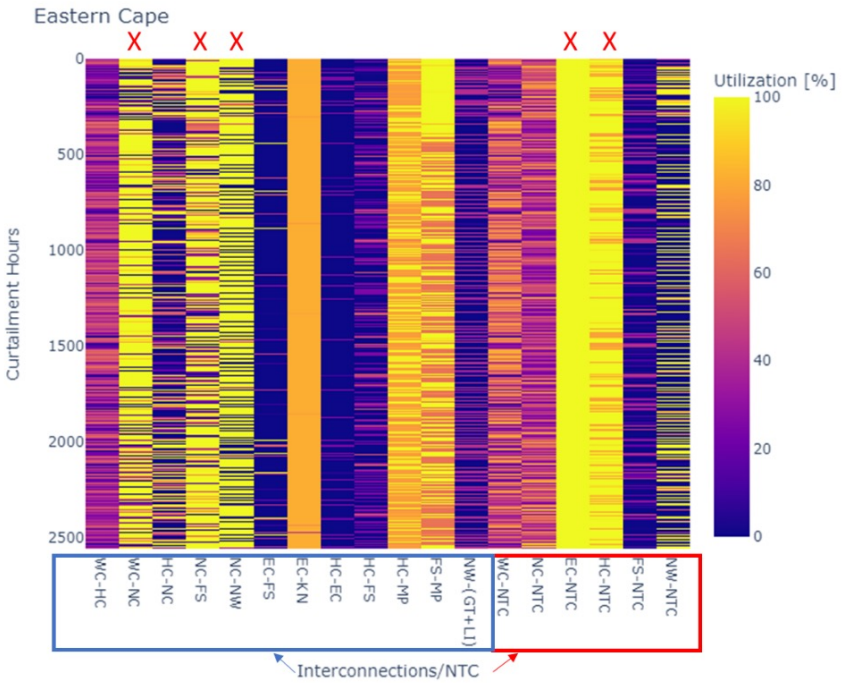
NC-FS	FS-MP	
92,5%	68%	

Most saturated NTC:

EC	HC	NW
99%	84,5%	72%

The NTC in NC is rarely exploited at its maximum limit.

The curtailment is caused by saturations occurring downstream, particularly on the interconnections with FS, and the limited NTC of EC, HC, and NW.



N curt. Hours: 2561

Most loaded lines:

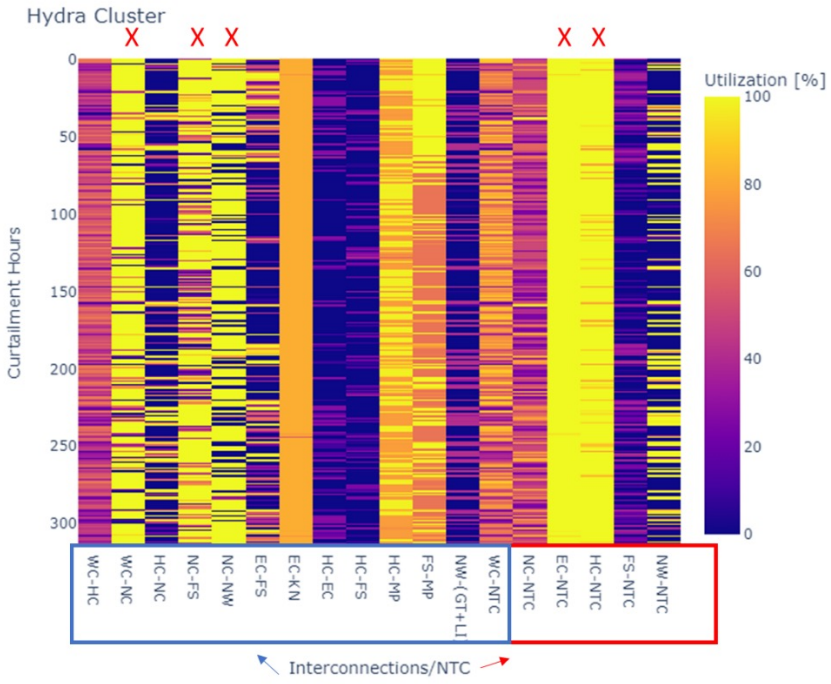
WC-NC	NC-FS	NC-NW
74,5%	61%	72%

Most saturated NTC:

EC	HC
100%	76%

Although the NTC in EC is always fully exploited at its maximum, the internal curtailment only occurs for 2561 hours. In the remaining, the local V-RES production is low, and the NTC is saturated by the flows that transit through EC towards KN.

The observed upstream high loading in the corridors of WC-NC, NC-FS and NC-NW are not expected to be deeply correlated with the curtailment hours in EC.



N curt. Hours: 315

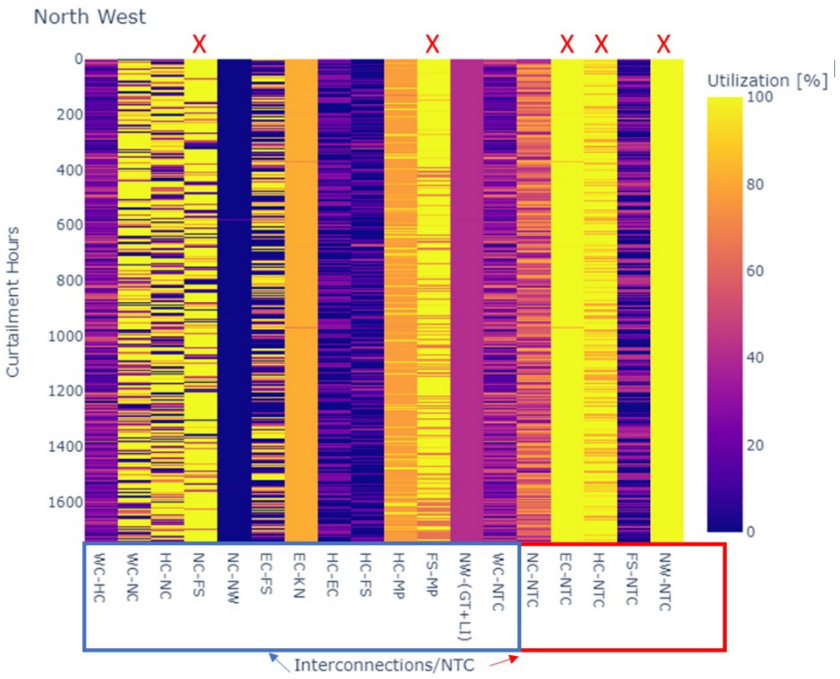
Most loaded lines:

WC-NC	NC-FS	NC-NW
79%	60%	74%

Most saturated NTC:

EC	HC
100%	92%

The NTC in HC is almost always fully utilised by the transit that flow in/out the area. In fact, the internal curtailment only occurs for 315, which is related to the low penetration of V-RES in the region. This constraint hence impacts on the possibility of the upstream supply areas to evacuate power.



N curt. Hours: 1752

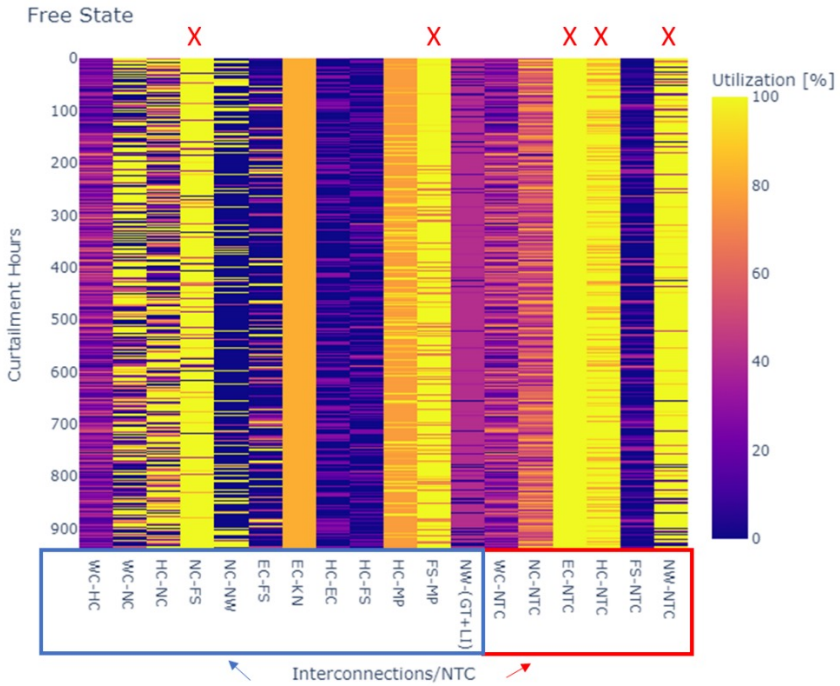
Most loaded lines:

NC-FS	FS-MP	
76%	77,5%	

Most saturated NTC:

EC	HC	NW
99%	76%	100%

Curtailment in NW could be almost entirely associated to the saturation of its limited NTC.



N curt. Hours: 943

Most loaded lines:

NC-FS	FS-MP	
88%	84%	

Most saturated NTC:

EC	HC	NW
100%	76%	86%

Curtailment in FS is predominantly caused by the full loading of the FS-MP corridor, and partially impacted by the impossibility to evacuate power through HC, whose NTC is already fully utilized.

Table 321 summarizes the correlation between the interconnections & NTCs saturation and the curtailment hours, highlighting with crosses (X) the corridors which are utilised more than 90% of their maximum limit for at least 60% of the curtailment hours in the corresponding supply area. The column "Hours of saturation" reports the total number of hours during which the Interconnection/NTC is utilized above 90% of its limit, and, in bracket, the subset of hours when also curtailment in one or more supply areas is experienced.

The following conclusions can be drawn:

- WC-NC and NC-NW corridors are almost fully loaded for around 80% of the time. However, only 40% of the time the saturation happens during curtailment hours, especially in WC, EC and HC.
- NC-FS is almost fully loaded for a lower amount of time but with a higher correlation to the curtailment hours of all the supply areas, 3076 out of 4357. Its impact on curtailment is hence similar or even higher than the other corridors.
- FS-MP is a corridor almost fully loaded for 67% of the time but only 2600 hours have an impact on the curtailment, mainly of the daily hours of FS.
- The NTC of EC is completely utilized for almost all the hours of the year. Solving this saturation is expected to considerably increase the possibility to evacuate power towards KN, and therefore to decrease the transit through FS and the related load on the FS-MP corridor.
- Similarly, the NTC of HC significantly impacts the transit flow towards the East side of the country, limiting the possibility to evacuate power from the Capes.
- The NTC of NW is significantly limiting the export of solar PV power from NC and NW itself.

	WC	NC	EC	HC	NW	FS	**Hours of saturation** (of which hours of curtailment)
WC-HC							0
WC-NC	X		X	X			6939 (3614)
HC-NC							1601 (1029)
NC-FS	X	X	X	X	X	X	4357 (3076)
NC-NW	X		X	X			6717 (2980)
EC-FS							1355 (450)
EC-KN							0
HC-EC							0
HC-FS							0
HC-MP							1943 (1553)
FS-MP		X			X	X	5867 (2600)
NW-(GT+LI)							0
WC-NTC							24
NC-NTC							73 (29)
EC-NTC	X	X	X	X	X	X	8707 (4880)
HC-NTC	X	X	X	X	X	X	6994 (4026)
FS-NTC							0
NW-NTC		X			X	X	2231 (2030)

Table 3-21 Summary of saturation on interconnections and NTCs

4 - CONCLUSIONS

This study aims at informing the next Eskom's GCCA development by calculating the maximum connection capacity of V-RES and BESS that can be integrated into the South African supply areas though an alternative energy-based approach that maximizes the contemporaneity between V-RES generation and load supply. This is done by building upon simulations that can consider the potential complementarity of PV, wind, storage, and load profiles during the days of the year, as well as a systematic V-RES curtailment practice. For each area, an energy optimisation of the supply-demand balance is performed, with the objective of maximising the export out of each supply area towards the East side of the country. The methodology followed two steps that envisaged the modelling of each separate supply areas (referred to as *Standalone Supply Areas* models), that adopted the GCCA 2024 data, and the modelling of the interconnected region (referred to as *Interconnected* model) of WC, EC, NC, HC, FS and NW based on GCCA 2025 data.

The conclusions from the different standalone supply areas and for the full interconnected model are reported below, together with an excursus on the main assumptions underlying the calculations through the different steps of the study, and a final section with the overall key-messages.

Standalone Supply Areas (GCCA 2024)

The first part of the study focuses on the modelling of the separated regions of Western Cape, Eastern Cape, Northern Cape, and Hydra Cluster, following GCCA 2024 (that was the latest available GCCA at the time the activities were performed). For the listed supply areas, the energy reference system composed by a generation, a load, an import, and an export bus are modelled, and simulated in accordance with five (5) different scenarios:

1. No BESS + No curtailment.
2. BESS 2GWh+ No curtailment.
3. No BESS + curtailment 10%.
4. BESS 2GWh + curtailment 10%.
5. BESS 3.2GWh + curtailment 10%.

All the above outcomes shall be considered in light of the fact that we only tested a limited size of BESS that was compatible with the target year (i.e., 2025). Therefore, the above results and conclusions on the BESS analysis must not be used to infer on the BESS advantages/disadvantages in the long run, which is out of the scope of the analysis.

The following outcomes are obtained:

- **Western Cape** is characterized by a good availability of wind resource, motivating a predominant installation of wind plants for all the scenarios (from 2100 MW to 4300 MW, depending on the scenario). ***Scenarios with 10% curtailment does bring the largest system benefits in terms of additional capacity to install and the consequent maximization of the exports***. On the other hand, ***BESS alone do not have a significant impact on the new installable V-RES capacity, but they allow to significantly increase the exported energy***. In addition, when properly optimized, the dispatching on the region would make the province an important net exporter.

- In **Eastern Cape**, only additional wind was considered, since the area is not considered particularly interesting for solar installations, resulting in a foreseen additional capacity from 1500 MW to 4100 MW, depending on the scenario. As said for Western Cape, ***the practice of 10% curtailment does bring the largest system benefits in terms of additional capacity to install and maximization of the exports. Also concerning BESS, the added value is very low***, since wind generation profile does not fit well with the daily charge/discharge behaviour of BESS.
- In **Northern Cape**, two additional cases are simulated: one with both PV and wind, and the other with only PV. Looking at the results, ***with neither curtailment nor BESS, the additional capacity of wind and PV is almost null, reflecting the current congested status of Northern Cape network***. The curtailment is much more beneficial to add wind capacity than new PV, which reflects the intrinsic properties of PV production (especially if provided with tracking) that presents daily energy production that is quite flat and persistent for more than 10% of the time. In the wind + PV scenario, BESS are used for peak shaving and for installing only new wind capacity. On the other hand, ***in the only PV scenario, the integration of BESS becomes crucial for expanding PV capacity***.
- Also in **Hydra Cluster**, two additional cases are simulated: one with the historical hydro generation profiles of Gariep Hydroelectric Power Station and Vanderkloof Hydroelectric Power Station, and the other with the optimized dispatch based on historical data on the river flows. The solution with the optimized dispatch of the hydro plants allows to slightly increase the penetration of V-RES, suggesting ***considering revising the current operational dispatching of Gariep and Vanderkloof plants***, if compatible with the existing water-release constraints.
- ***In all the supply areas, the 10%-curtailment practice brings the largest marginal additional benefits to unlock and increase the V-RES capacity, especially for wind.***
- On the **BESS**, it results that the in a deeply constrained situation – as present in South Africa – where the curtailment practice is not allowed, the introduction of BESS allows to integrate more V-RES, whose additional production allow to off-set the cost of BESS itself. This is especially ***evident in Western Cape***, followed by Northern Cape, Hydra Cluster, and then Eastern Cape. ***Northern Cape results to be the area where BESS allow to achieve the largest relative increase of new V-RES capacity, and where the BESS is utilized the most (cycles- and energy-wise) in case of no curtailment***. In general, from a pure energy-perspective, the results do not reveal any specific area as being particularly more suitable than others for the installation of BESS. Therefore, the analysis suggests that: 1) the areas with no carrying capacity available and the areas with system balancing and ROCOF issues should be prioritized; 2) where there are less balancing/inertia problems and available supply area capacity, the curtailment outperforms the BESS advantages in terms of increasing V-RES penetration, and it should be privileged with respect to BESS installation. On the BESS scenarios, it is important to highlight that the limited amount of capacity tested in the parametric analysis and the related results are to be intended and interpreted in light of the fact that we only tested a limited size of BESS that was compatible with the target year (i.e., 2025). Therefore, the above results and conclusions on the BESS analysis must not be used to infer on the BESS advantages/disadvantages in the long run, which is out of the scope of the analysis.

Full Interconnected Model (GCCA 2025)

In the Interconnected model, the Western Cape, Northern Cape, Eastern Cape and Hydra Cluster supply areas previously modelled are fine-tuned based on the GCCA 2025 data and information. They are then interconnected with the possibility to exchange energy (import/export), and they are integrated with Free State and North West. The interconnected region is linked with the "sink" areas of Mpumalanga, KwaZulu Natal, Gauteng, and Limpopo, which are modelled according to their supply capacity derived

from the GCCA 2025. The interconnecting corridors among the supply areas are modelled considering the maximum flow represented by the surge impedance loading of each interconnection line.
The model is simulated and investigated through two (2) scenarios: the "Base case" with 500 MW/2 GWh BESS only in Northern Cape and the "Base + BESS in NW and FS" with the integration of 615 MW/2.46 GWh BESS also in North West and Free State.

The following outcomes are obtained:

- In **Western Cape**, it is feasible to install 2031 MW of wind in the Base case, while it slightly increases up to 2056 MW with BESS in North West and Free State. PV power is not expected to be installed in the region. This result shall be interpreted at the light of the objective of the optimization performed in PLEXOS, that is the maximization of the exports towards the East regions. ***The corridor linked to Hydra Cluster is primarily used for exporting surplus generation*** that exceeds the local demand.

- Also in **Eastern Cape**, V-RES installations are characterized only by wind power: 1011 MW for the base case and 1028 MW for the case with BESS in North West and Free State. ***This additional capacity results to be largely limited by the low NTC of the region, which considerably constraints the export from the area, and therefore the installable wind capacity***. The region imports both from Free State (around 60%) and Hydra Cluster, and exports to the external area of KwaZulu Natal.
- In **Northern Cape**, the additional ***V-RES capacity remains minimal, due to the limited hosting capacity of the Northern Cape network***. Only a modest amount of wind capacity, approximately 338 MW, can be integrated in the region. The supply area imports from Western Cape mainly for satisfying its load. The interconnection with Free State is used for both import and export, but the largest exports are through the corridor with North West.
- ***No additional V-RES capacity is installed in Hydra Cluster***, reflecting its status as a transit area, which ***presents critical internal congestions that are preventing endogenous new V-RES capacity and limiting the evacuation of power from the Capes***. More than 70% of the import capacity is coming from Western Cape, while slightly less than 90% of the export goes to Mpumalanga.
- In **Free State and North West**, only PV is expected to be integrated. ***The incorporation of BESS in these regions facilitates a substantial increment in the potential for PV installations for the internal supply-demand balance***, which plays a pivotal role for the reduction of the endogenous coal plant usage in Free State and the import of power (mainly thermal-based) in North West. For what concerns the external areas, **Mpumalanga** is connected to Free State and Hydra Cluster, and its maximum import capacity (3320 MW) is saturated almost all the hours of the year, acting as the main "outlet" of the V-RES production from the inner regions. During the light hours, the saturation is by far attributable to the V-RES production. This suggests the following interesting output: ***the capacity freed-up by the expected decommissioning of coal power plants in MP would serve to increase the production and evacuation of more V-RES import, especially the PV production during the day. This reduces the room and interest for a direct replacement of the coal plants with local PV installations in MP, while wind may be a more interesting option to investigate***. **KwaZulu Natal** is connected only to Eastern Cape, and ***its import is largely constrained by the NTC of this region. The export towards Gauteng and Limpopo is limited by the NTC of North West***, which reflects the fact that the corridor is only used to evacuate the extra PV generation from North West, since the import from Northern Cape is only used to satisfy the internal North West load.
- Additional simulations are performed for both the scenarios with and without BESS in North West and Free State to test the what if situation without the 10% curtailment practice. The results show that ***curtailment is definitively benefitting new wind capacity, by unlocking GWs of new installations***

that would otherwise be unable to be connected. Without curtailment, basically no additional wind could be potentially installed in the Capes. In addition, ***curtailment is increasing new overall wind production more than 50%***. As expected, ***benefits are limited for PV plants, for which the 10%-curtailment practice is increasing by around 2-4% the production***.

- There ***may be the need to build a proper incentives-based scheme*** in parallel to curtailment, which, e.g., may redistribute the expected benefits achievable from the massive increase of the low-cost V-RES production gained through the 10%-curtailment practice back to the IPPs that would otherwise experience individual losses of earnings and, expectably, may increase their off-take tariffs to compensate them.
- With respect to a carpet 10%-curtailment to all the V-RES fleet (existing and new), ***it should be considered the possibility to implement a punctual and optimized 10%-curtailment to address the most critical power parks in the most critical areas and situations***, that, when curtailed in some circumstances, may bring the highest overall system benefits.
- We tested an additional scenario with 10%-curtailment applied to wind only, in order to consider the uncertainty related to the nature of future PV installations (i.e., utility-scale vs rooftop PV, the latter considered as "uncurtailable"). Results demonstrate that ***the 10%-curtailment applied to wind only would allow to achieve similar system benefits than the 10%-curtailment practice applied to both PV and wind***.
- We introduced an analysis to identify the most saturated corridors and supply areas. In particular, ***the connection between Northern Cape and Free State*** is highly constraining the system and seems impacting on the curtailment in all areas. ***The interfaces between Western Cape-Northern Cape and the Northern Cape-North West are saturated for most of the year***, indicating that ***releasing such constraints would benefit the possibility to evacuate power through the entire upper corridor from Western Cape to North West***. At the same time, ***the limited NTCs of Eastern Cape and Hydra Cluster are blocking the possibility of higher V-RES installations in the whole country***. Being this analysis a purely energy optimization, it does not reflect the actual "impedance map" of the grid that might give different results. Therefore, these conclusions shall be read as possible indications that hint at possible corridors/areas that may be worth to be investigated in consequent network simulations.

Overall conclusions and key-messages

In conclusion, the study allows to highlight the following key-messages:

1. The adopted approach confirms that building upon the possible complementarity of the PV and wind and the contemporaneity of V-RES output with load demand, a proper integration of BESS, and a prudent application of curtailment would allow to unlock a significant additional amount of new V-RES, that would be otherwise prevented in almost all the Western supply areas.
2. In terms of dispatching and operation, the point above translates into the need to possibly revise the dispatching processes of ESKOM to properly manage the complex challenges imposed by a system that is becoming increasingly decarbonized. For example: with new V-RES penetration, the time period where the grid usage is maximised is likely to be during the daily hours (when PV is on), and this will require to consider revising the operational planning practices and optimizing maintenance during the night hours. Similarly, also pumped-hydro-storages and hydro plants dispatching profiles should be re-optimized to better accommodate and maximize V-RES production.
3. Curtailment practice brings substantial system benefits, that, up to a certain extent, would be otherwise reachable only through uneconomical grid investments. All the stakeholders involved in the various sectors of the full electricity-supply chain would benefit from a wise and optimized application of

curtailment: the IPPs-sector would gain from the increased available supply area capacity "unlocked" by curtailment; ESKOM, as system operator, would increase the available resources to dispatch the system, solve congestion, and balance the system; consumers would benefit from an expected increase in the security-of-supply (reduced load shedding), a more decarbonized system and possible reduction in the cost of electricity.

4. Our results show that the expected benefits achievable from the massive increase of low-cost V-RES production that can be reached by curtailment (around +20%) can be the driver to remunerate back the deemed-but-not-evacuated energy (e.g., for existing IPPs) and/or to cover the expected increase the off-take tariff to compensate the possible losses of earnings (e.g., for new IPPs). However, any implementation scheme of the curtailment practice shall consider all the obligations that ESKOM has in terms of guaranteeing of the minimum levels of network availability (non-compliance with which generates the curtailment need) and the contractual arrangements with the existing IPPs. Carefulness and attention should be paid to avoid discrimination between IPPs that are operating under different contract frameworks and conditions imposed by curtailment (e.g., operating IPPs vs IPPs in constructions with already-signed PPA vs future RMIPPPP).
5. Future rooftop PV penetration should be carefully addressed and wisely investigated, since it has a huge impact on the need and capacity to accommodate additional utility scale PV and on the expected benefits of the curtailment practice.
6. The results clearly reveal that, although they bring substantial benefits to the system, curtailment and BESS alone does not off-set the limitations imposed by the existing congested network topology, which remains an important limiting factor to a further increment of V-RES, needed to couple the gradual and expected decommissioning of thermal power plants in the East side. This still calls for strategic investments in reinforcing both the internal network components and some strategic inter-areas corridors.
7. Given the complexity of investigating the operation of power systems, the results achieved with this energy-based study require further iterations with additional network studies to be validated also from a power system perspective.


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