Wind and Solar PV Resource Aggregation Study for South Africa

Public presentation of results

Pretoria, 3 March 2016

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Dr. Tobias Bischof-Niemz, Crescent Mushwana – CSIR
Acknowledgements and contributions

Working group:
SAWEA
SAPVIA
DoE IPP Office
GIZ SAGEN
DoE
DANIDA/DoE
Energy Exemplar

Study was conducted from early 2015 to March 2016
Executive Summary

CSIR, SANEDI, Eskom and Fraunhofer IWES conducted a study to holistically quantify

- the wind-power potential in South Africa and
- the portfolio effects of widespread spatial wind and solar power aggregation in South Africa

Wind Atlas South Africa (WASA) data was used to simulate wind power across South Africa

Key result: South Africa exhibits world-class conditions to introduce very large amounts of variable renewables into the electricity system

- Both solar and wind resources are world class: solar PV and wind turbines are therefore very low-cost bulk energy providers in South Africa already today
- Both solar and wind supply have very low seasonality in South Africa
- Very wide-spread interconnected electricity grid enables spatial aggregation to reduce volatility
- South Africa is a very large country with low population density: space is not a constraint
- Turbines widely dispersed: Even 50% wind energy share does not create short-term volatility
Agenda

1. Introduction
2. Data
3. Methodology
4. Scenarios
5. Results
6. Conclusions and Outlook
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   I. Fraunhofer IWES
   II. CSIR Energy Centre
   III. Motivation
   IV. Objectives of the study

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6. Conclusions and Outlook
Main Research:
- Wind energy from material development to grid optimization
- Energy system technology for all renewables

Fraunhofer IWES | Kassel
Director: Prof. Dr. Clemens Hoffmann

Fraunhofer IWES | Northwest
Director: Prof. Dr. Andreas Reuter

Annual budget: approx. EUR 30 millions

Staff: approx. 500
Fraunhofer IWES
Energy System Technology, Kassel

R&D for the success of the German „Energiewende“ and the global use of renewable energy
Core Skills for Energy System Technology

Energy Economy and System Design

System Integration

Energy Grids

Energy Informatics

Energy Storage System Technology

Energy Meteorology and Renewable Resources

Energy System Technology
Introduction IWES – Kassel Site: Energy System Technology

- Energy Economy and Grid Operation
- Energy Economics and System Design
- Energy Scenarios and System Modelling
- System Engineering and Distribution Grids
- Wind Farm Planning and Operation
- Business Models and Market Integration
- Transmission Grids
- Energy Process Technology
- Energy Informatics and Information Systems
- Energy Economics and System Analysis
- Energy Scenarios and System Modelling
- Wind Farm Planning and Operation
- Business Models and Market Integration
- Transmission Grids
- Energy Process Technology
- Energy Informatics and Information Systems
- Energy Economics and System Analysis
IWES team

Project lead and management

Scientific supervision
Curtailment
Skills exchange

Dr. Stefan Bofinger

Case study I
Results analysis
Skills exchange

Britta Zimmermann

Data processing
Spatial distribution
Aggregation of time series

Kaspar Knorr

Data processing
Wind time series
Skills exchange

Ann-Katrin Gerlach

Data processing
PV time series

Mirjam Stappel

Demand
Forecast

Rainer Schwinn

Jan Dobschinski
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The CSIR’s Executive Authority is the Minister of Science and Technology

The CSIR is a science council, classified as a national government business enterprise, with six sites across South Africa, headquartered in Pretoria

The CSIR in numbers

- 70 years (established 5 October 1945)
- Close to 3 000 total staff
- …of which 1 700 scientists, engineers & technologists
- …of which more than 300 doctoral qualifications
- 8 research centres/units, three implementation units
- ~ $200 million total operating income per year
  (~30% government grant to invest into new topics, ~70% through contract research)
CSIR’s six Research Impact Areas (RIAs) respond to the priorities as defined by South Africa’s “National Development Plan (NDP)”

**Core technologies & facilities**

- Materials
- Sensors
- Photonics
- Robotics
- ICT
- Modelling
- Research facilities

**Domains**

- Industry
- Health
- Energy
- Defence & Security
- Natural Environment
- Built Environment
CSIR’s new Energy Centre streamlines and expands CSIR’s energy research offerings in five areas – today: 20 staff members, growing

Potential 6th area: Industry Business Cases

CSIR Energy Centre research areas

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>• Energy Efficiency in all end-use sectors</td>
<td>• Solar</td>
<td>• Energy Storage (Power-to-Power, Power-to-Heat)</td>
<td>• Energy Planning</td>
<td>• Macro- and Energy Economics</td>
</tr>
<tr>
<td>• Demand forecasting</td>
<td>• Wind</td>
<td>• Power-to-Hydrogen</td>
<td>• Grid Planning</td>
<td>• Clean Energy Markets (RE and Natural Gas)</td>
</tr>
<tr>
<td>• Demand response</td>
<td>• Biomass/-gas</td>
<td>• Power-to-Gas</td>
<td>• Micro and Island Grids</td>
<td>• Regulatory Environment and Market Design</td>
</tr>
<tr>
<td>• Energy statistics</td>
<td>• Liquid Biofuels</td>
<td>• Power-to-Liquids</td>
<td>• System Operations</td>
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<td></td>
<td>• Small Hydro</td>
<td>• Electric Mobility</td>
<td>• Smarter Grids</td>
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<td></td>
<td>• Ambient Heat</td>
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</tbody>
</table>

CSIR Energy-Autonomous Campus
(cross-cutting demonstration programme)

Five year objective: approx. 100-120 staff to be able to address all relevant dimensions of RSA’s energy transition

Sources: CSIR Energy Centre analysis
The CSIR Energy Centre’s vision and mission

Vision
“To provide the knowledge base for the South African energy transition and beyond”

Mission
The Energy Centre’s activities are guided by the desire to help developing a sustainable energy system, more specifically:

• To conduct directed research in emerging energy technologies and system integration
• To prove the concept of emerging energy technologies and of integrated energy systems
• To demonstrate energy technologies and systems in the South African context and to support their commercialization
• To conduct directed research towards the understanding of how to optimally design, build and operate cost efficient, reliable and sustainable energy systems
• To find optimal pathways for the expansion and operation of energy systems through modelling and simulation
• To advise policymakers on market design and regulatory concepts for the integration of new energy technologies
• To provide support for South African industries on key energy-system-related decisions
• To provide thought leadership for the energy research agenda in South Africa and in the region
• To be globally recognised as the premier applied-energy-research organisation on the African continent
CSIR Energy Centre team as of 7 March 2016

Sources: CSIR Energy Centre analysis
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Africa has some of the best solar resources worldwide
Southern Africa also has some of the best wind resources
South Africa has almost two times the solar resource of Germany, where solar PV is close to cost competitiveness.

Solar resource in South Africa... ... as compared to Germany

SA’s planned PV capacity by 2030: 8.4 GW

Germany’s status today: almost 40 GW installed solar PV capacity (roughly one Eskom)
Best wind sites in Germany along the coastline have similar wind speeds as large parts of inland South Africa (yellow)

Wind resource in South Africa… … as compared to Germany

SA’s planned wind capacity by 2030: 9.2 GW
Germany’s status today: almost 46 GW installed wind capacity (roughly one Eskom)
In less than two years, South African PV has outpaced the US

Share of solar PV in electricity production

<table>
<thead>
<tr>
<th></th>
<th>2013</th>
<th>2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>USA</td>
<td>0.2%</td>
<td>0.4%</td>
</tr>
<tr>
<td>RSA</td>
<td>0.0%</td>
<td>1.0%</td>
</tr>
</tbody>
</table>

Sources: EIA; CSIR
Even within a small area around Port Elizabeth, aggregation effect for both solar PV and wind power output clearly visible

21 September 2011: Simulated output for five individual wind and PV sites and for entire PE region
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Objectives of the study

Main goal: Increase the fact base and understanding of aggregated wind and solar PV power profiles for different spatial distributions of wind turbines in South Africa

• Generate data sets that can be used for various studies (IEP, IRP, TDP, SEA etc.)
• Transfer of knowledge and skills on utilising wind data in energy-planning activities

Resulting in

• Confidence in integrating higher RE shares
• Basis for further research, e.g. defining an optimal RE mix, system adequacy & reserve margin

The study was conducted from early 2015 to March 2016 and covers whole of South Africa

• Wind and solar data sets covering the entire country
• 5x5 km spatial resolution, 15 minute time resolution, 5 years of data
• Spatial load data for the entire country
Side Tasks

- Sufficiency analysis
- Curtailment analysis

WIND AND SOLAR AGGREGATION STUDY SOUTH AFRICA

Data for IRP, ESKOM, GIZ

Skills exchange
Publications issued during the course of the study
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Raw data: time- and spatially synchronous wind and solar data produced from reliable raw-data sources (WASA&SODA)

<table>
<thead>
<tr>
<th>Model name</th>
<th>WASA</th>
<th>SODA</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Variables</strong></td>
<td>Wind speed, temperature</td>
<td>Solar irradiation</td>
</tr>
<tr>
<td><strong>Height</strong></td>
<td>50 m, 80 m, 100 m, 150 m (v)</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>2 m (T)</td>
<td></td>
</tr>
<tr>
<td><strong>Temporal coverage</strong></td>
<td>2009 to 2013</td>
<td>2010 to 2012</td>
</tr>
<tr>
<td><strong>Temporal resolution</strong></td>
<td>15 min</td>
<td>15 min</td>
</tr>
<tr>
<td><strong>Spatial coverage</strong></td>
<td>South Africa</td>
<td>South Africa</td>
</tr>
<tr>
<td><strong>Spatial resolution</strong></td>
<td>5 km x 5 km</td>
<td>0.2° x 0.2° (similar to 5 km x 5 km)</td>
</tr>
</tbody>
</table>
South Africa has wide areas with > 6 m/s average wind speed

Average wind speed at 100 meter above ground for the years from 2009-2013 for South Africa
Validation: Is a 5x5 km² resolution of weather data sufficiently high for the purposes of this aggregation study?

- Evaluating simulation results (= feed-in)
- Step 1: Considering every pixel
- Step 2: Considering every second pixel
- Step 3: Considering every third pixel
- ...

approximate pixel distance: 50km
approximate pixel distance: 100km
approximate pixel distance: 150km
approximate pixel distance: 350km
Fluctuations of aggregated wind power stay constant below 50 km pixel distance $\rightarrow$ resolution of 5x5 km high enough

Results for different starting pixels

Stable behaviour
Fluctuations of 15-min ramps of aggregated wind power stay constant below 20 km pixel distance → 5x5 km sufficient

- Resolution below 20x20 km² seems to be sufficient for a nation-wide study
- For actual plant design and techno-economical viability studies higher resolution data could be necessary
Demand: Historical spatially available load data scaled to match estimated future country demand of 500 TWh/yr

Raw data used (source: Eskom)

- Historical data for entire country
- Spatially distributed across transmission substations (present: 2014 and future: 2024)
- Temporal coverage: years from 2010-2012
- Temporal resolution: 30 min but (interpolated to an 15-min resolution to match solar/wind data)
- Current total country demand: ~225 TWh/yr

Future estimated demand: 500 TWh/yr

→ Scaled on demand of single grid Nodes and allocated to grid nodes
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Core study approach:
Simulated wind/PV and historical load jointly analysed

Weather data from weather models

Generation of wind and PV time series: Potential electricity generation

Spatial distribution scenarios: wind and PV

Aggregation of wind and PV time series

Residual load time series for each scenario

Quantification of aggregated profiles

Historical electricity demand

Future electricity demand
Generic wind turbines defined with applicability for different wind-speed regimes: basis for wind farm design per pixel

<table>
<thead>
<tr>
<th>Turbine type no.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal power</td>
<td>3 MW</td>
<td>2.2 MW</td>
<td>2.4 MW</td>
<td>2.4 MW</td>
<td>2.4 MW</td>
</tr>
<tr>
<td>Rotor diameter</td>
<td>90 m</td>
<td>95 m</td>
<td>117 m</td>
<td>117 m</td>
<td>117 m</td>
</tr>
<tr>
<td>Swept rotor area</td>
<td>6 362 m²</td>
<td>7 088 m²</td>
<td>10 750 m²</td>
<td>10 750 m²</td>
<td>10 750 m²</td>
</tr>
<tr>
<td>Power per swept area</td>
<td>442 W/m²</td>
<td>310 W/m²</td>
<td>223 W/m²</td>
<td>223 W/m²</td>
<td>223 W/m²</td>
</tr>
<tr>
<td>Hub height</td>
<td>80 m</td>
<td>80 m</td>
<td>100 m</td>
<td>120 m</td>
<td>140 m</td>
</tr>
<tr>
<td>Selection criterion</td>
<td>øv @ 80 m &gt; 8.5 m/s and øv @ 100 m &gt; 7.5 m/s</td>
<td>øv @ 80 m &lt; 8.5 m/s</td>
<td>øv @ 100 m &lt; 7.5 m/s</td>
<td>øv @ 120 m &lt; 7.5 m/s</td>
<td>øv @ 140 m &lt; 7.5 m/s</td>
</tr>
<tr>
<td>Turbine type</td>
<td>High wind speed</td>
<td>Medium wind speed</td>
<td>Medium to low wind speed</td>
<td>Low wind speed</td>
<td>Low wind speed</td>
</tr>
</tbody>
</table>

Space requirement 0.1 km²/MW → max. 250 MW per pixel
In each of the 50 000 pixels of 5x5 km size across the country, a wind farm placed consisting of turbines of type 1, 2, 3, 4 or 5...
Power curves of single wind turbines (top) and for simulated wind farms on a 5km x 5km pixel (bottom) by turbine type

Wind turbine characteristic as taken from data sheets

For considering wind farm effects (shading, wake) as well as simulating the aggregation / smoothing within the 5x5 km² areas, smoothed wind turbine power curves defined and applied per pixel.
Generation of time series of wind feed-in

Turbine information

- location (lat, long)
- power curve
- hub height
- meteorol. year
- parameter

Smoothing function

Smoothed power curve

Simulation of power time series

- define pixel of weather model
- pixel
- prepare windspeed
- windspeeds at hub height
- consider shading effects
- windspeeds reduced by shading
- adjust wind speeds
- windspeed to power
- windspeeds reduced by η_v
- adjust power
- reduced power
- feed-in

Results

Time series of wind power per pixel
Share of each 5x5 km² pixel that is suitable for installation of wind farm after excluding areas reserved for other functions

Exclusion masks sourced from the Department of Environmental Affair’s Wind and solar PV REDZ study (conducted by the CSIR)

Note: Within the Mpumalanga area (dark red area in the map) data are incomplete. Therefore larger areas are assumed to be suitable. In reality, more exclusion areas will be found. Due to the low wind resources in the Mpumalanga area the impact on the final results should be insignificant.
Definition:
“Residual load” needs to be supplied by dispatchable power

\[
\text{Residual load } (t) = \text{Load } (t) - \text{PV feed-in } (t) - \text{Wind feed-in } (t)
\]

From demand to residual load

Hour of the day

00 04 09 14 19 00

Min

Max

\(\Delta t\)

\(\Delta P\)

Gradient

Load
PV feed-in
Wind feed-in
Residual load
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Three solar PV and three wind penetration levels defined
Overview of combination of solar PV and wind scenarios; load scaled to 500 TWh/yr total electricity

<table>
<thead>
<tr>
<th>Solar PV energy penetration (one fixed spatial distribution defined)</th>
<th>Wind energy penetration</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>50 TWh/yr (~15 GW)</strong></td>
<td><strong>100 TWh/yr (~30 GW)</strong></td>
</tr>
<tr>
<td>40 TWh/yr (~21 GWp)</td>
<td>• VRE Share: 18%</td>
</tr>
<tr>
<td></td>
<td>• 9 Wind distribution scenarios</td>
</tr>
<tr>
<td>80 TWh/yr (~42 GWp)</td>
<td>• VRE Share: 26%</td>
</tr>
<tr>
<td></td>
<td>• 9 Wind distribution scenarios</td>
</tr>
<tr>
<td>200 TWh/yr (~104 GWp)</td>
<td>• VRE Share: 44%</td>
</tr>
<tr>
<td></td>
<td>• 9 Wind distribution scenarios</td>
</tr>
</tbody>
</table>

Note: VRE = variable renewable energy, which is solar PV and wind (the only two variable power sources; dispatched by the weather and not the owner / system operator) VRE share is calculated on the basis of „useful VRE per total electricity demand“, i.e. curtailed VRE is not considered in these numbers
Scenarios: for each wind-energy penetration level 9 scenarios of different spatial distribution of the wind fleet are tested

‘Scientific’ scenarios

1a Uniform wind turbine distribution
1b All-in-one-place
1c High wind speeds wind turbine distribution
1d Minimal ramps wind turbine distribution

Designated areas investigated

2a EIA\(^1\)-focused wind turbine distribution
2b REDZs\(^2\)-focused wind turbine distribution
2c EIA/REDZs overlaps

Grid-oriented scenarios

3a Current grid-focused wind turbine distribution
3b Future grid-focused wind turbine distribution
Present and future grid nodes for grid-oriented scenarios and the individual location selected for ‘All-in-one-place’ scenario

Location 'All-in-one-place'

Present grid node
Future grid node

Longitude
Latitude

Cape Town
Kimberley
Welkom
Port Elizabeth
Bloemfontein
Durban

East London
Johannesburg
Nelspruit
Polokwane
Upington

Location 'All-in-one-place'

Present grid node
Future grid node
Areas used for the designated-areas scenarios
In order to achieve 50, 100, 250 TWh/yr of wind electricity, ~15 GW / ~30 GW / ~75 GW of wind power need to be installed.

→ 50 TWh/yr of wind electricity requires 1 500 km² = 0.12% of South Africa’s landmass
→ 250 TWh/yr of wind electricity requires 7 500 km² = 0.61% of RSA’s landmass
Only a small portion of wind farm area is actually utilised land
Illustration of space consumed by wind farms in a 250 TWh/yr wind energy scenario

- Entire South African land mass
- Usable land (after exclusion zones)

Wind farms’ area for 250 TWh/yr
(0.61% of South Africa’s land mass)

- Pathways, foundations, etc. during construction
- Pathways, foundations, etc. during operation
- Wind turbine foundations
During construction, actual land used is already low
Illustration of land required during construction of a wind farm
During wind farm operation, the land actually used is very low

Illustration of land required during operation of a wind farm

<table>
<thead>
<tr>
<th></th>
<th>% of the wind farm area</th>
<th>% of South African land mass (for a 75 GW wind fleet that yields 250 TWh/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind farm area</td>
<td>100%</td>
<td>0.61% (7 500 km²)</td>
</tr>
<tr>
<td>Ways, foundation during construction</td>
<td>3%</td>
<td>0.018% (225 km²)</td>
</tr>
<tr>
<td>Permanently used</td>
<td>2%</td>
<td>0.012% (150 km²)</td>
</tr>
<tr>
<td>Wind turbine foundations</td>
<td>0.1%</td>
<td>0.0008% (10 km²)</td>
</tr>
</tbody>
</table>
The total solar PV potential in South Africa from distributed installations & utility-scale in already applied EIAs is 300 GW

Distributed solar PV (rooftop only)
- 73 GW installed capacity
- 136 TWh/yr electricity generation

Utility-scale solar PV (in EIAs only)
- 220 GW installed capacity
- 420 TWh/yr electricity generation

Total potential (rooftop and EIAs only)
- 292 GW installed capacity
- > 550 TWh/yr electricity generation

Additional potential: distributed small and medium ground-mounted

Note: The potential for distributed solar PV is based on very conservative estimates for achievable penetration with rooftop solar PV in settlement areas. It is assumed that 10% of the total settlement area are rooftops which can in principle be used for solar PV. The potential needs to be further quantified in subsequent studies.
Solar PV defined as a mix of distributed and utility-scale

- 70% of the annual electricity is generated by distributed solar PV installations
- 30% of the annual electricity is generated by large, utility-scale installations

<table>
<thead>
<tr>
<th></th>
<th>Penetration level 1</th>
<th>Penetration level 2</th>
<th>Penetration level 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distributed (70%)</td>
<td>15 GW</td>
<td>29 GW</td>
<td>73 GW</td>
</tr>
<tr>
<td>Utility scale (30%)</td>
<td>6 GW</td>
<td>13 GW</td>
<td>31 GW</td>
</tr>
<tr>
<td>Total</td>
<td>21 GW</td>
<td>42 GW</td>
<td>104 GW</td>
</tr>
</tbody>
</table>

1. „Distributed“ is a proxy for all PV that is assumed to be distributed according to population density. It represents all PV close to the load which in this study would include only rooftop PV in all sizes. In reality, distributed PV could also include small ground-mounted installations.

2. “Utility-scale” is a proxy for large-scale PV installations in the multi-MWp-range, for which EIAs have been applied for.
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Case study:
Supply areas of South Africa

The South African transmission grid is divided into 27 supply areas.

Each supply area comprises several grid nodes.

The size of the supply areas is determined by the total customer load.

→ Supply areas with load centres usually include a high number of nodes in a small area.
Case study:
Aggregation effects within the supply area of Port Elizabeth
Case study: Spatial aggregation smoothens volatility
Simulated supply of 5 solar, 5 wind farms & of the entire Port Elizabeth area on 21 March 2011
Case study: Spatial aggregation smoothens volatility
Simulated supply of 5 solar, 5 wind farms & of the entire Port Elizabeth area on 21 June 2011
Case study: Spatial aggregation smoothens volatility
Simulated supply of 5 solar, 5 wind farms & of the entire Port Elizabeth area on 21 September 2011
Case study: Spatial aggregation smoothens volatility
Simulated supply of 5 solar, 5 wind farms & of the entire Port Elizabeth area on 21 December 2011
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6. Conclusions and Outlook
Solar PV monthly supply has very low seasonality, wind supply more in winter: correlated to the load

Simulated solar PV, wind, scaled load – grid-focused wind distribution: 250 TWh/yr, PV: 80 TWh/yr

→ PV: nearly no seasonality

→ Monthly wind supply is correlated with the monthly fluctuations in demand
Average wind profile generally with less output during the day and more during evening/night – complements well load & PV

Simulated solar PV, wind, scaled load – grid-focused wind distribution: 250 TWh/yr, PV: 80 TWh/yr
Average wind profile generally with less output during the day and more during evening/night – complements well load & PV

Simulated solar PV, wind, scaled load – grid-focused wind distribution: 250 TWh/yr, PV: 80 TWh/yr
Definition of load factor: Total energy produced during a time period divided by (nominal power multiplied by time period)
Definition of load factor: Total energy produced during a time period divided by (nominal power multiplied by time period)
Placing a wind farm of best suited turbine type (1, 2, 3, 4 or 5) in each pixel: more than 30% load factor almost everywhere

→ Very high load factors of >30% nearly all over the country!
Even when placing only high-wind-speed turbine types (1, 2, 3) in each pixel: more than 30% load factor in very wide areas

→ Very high load factors of >30% nearly all over the country even for turbines types 1-3
On almost 70% of suitable land area in South Africa a 35% load factor or higher can be achieved (>50% for turbines 1-3)

Share of South African land mass less exclusion zones with load factors to be reached accordingly

→ Installing turbine type 4 and 5 will cause higher costs but also increase load factors and electricity yield whilst consuming the same area
Achievable load factors in all turbine categories significantly higher than actual load factors in leading wind countries

Load factors by turbine type across all 50,000 pixels for South Africa for years 2009-2013

- Years: 2009-2013

Actuals Spain (installed capacity: ~23 GW)

Actuals Germany (installed capacity: ~46 GW)
A single wind farm changes its power output quickly
Simulated wind-speed profile and wind power output for 14 January 2012
Aggregating just 10 wind farms’ output already reduces short-term fluctuations
Simulated wind-speed profile and wind power output for 14 January 2012
Aggregating 100 wind farms: 15-min gradients almost zero
Simulated wind-speed profile and wind power output for 14 January 2012
Aggregation across entire country: wind output very smooth
Simulated wind-speed profile and wind power output for 14 January 2012
In all scenarios, achievable load factors are very high

→ Very high load factors for all scenarios
→ „Minimal ramps“ optimization leads to lower ramps but also to lower load factors
Wide spatial wind distribution leads to smooth duration curve

Aggregated wind power duration curves for different scenarios for years 2010-2012

→ Wider distribution leads to smoother wind-power duration curves
→ With a wider distribution there is residual electricity feed-in at all times
Excess energy only occurs with very high wind penetration
Duration curves of residual load for “grid-focused wind turbine distribution” for different penetrations

→ Wind feed-in reduces the residual load at almost every moment
→ Electricity surplus occurs at very high wind penetration only

Residual load = Load – PV feed-in – Wind feed-in
Solar PV: excess steeply increases above certain penetration

Duration curves of residual load for “grid-focused wind turbine distribution” for different penetrations

→ High PV shares leads to high electricity surpluses
→ Base load disappears
Max. residual load significantly lower than max. system load
Maximum residual load for different scenarios with PV: 80 TWh and different wind penetration levels

→ A higher installed capacity decreases maximum residual load
→ Installed capacity of PV does not have an influence

Max. load: 77 GW
Spatial distribution reduces 15-minute gradients drastically
Relative frequency of 15-min gradients of residual load for different wind spatial distribution

- 100 TWh of electricity from wind energy and 40 TWh from PV
Short-term fluctuations of residual load quantified for different penetration with wind and solar PV

Standard deviation of 15-min gradients of residual load for different wind penetrations and scenarios
15-min gradients do not increase with higher wind penetration

Standard deviation of 15-min gradients of residual load for different wind penetrations and scenarios

![Graph showing the standard deviation of 15-min gradients of residual load for different wind penetrations and scenarios.](image)

- **No wind energy**
- **Uniform**
- **All in one place**
- **High wind speed**
- **Minimal ramps**
- **Grid-focused**

**Parameters:**
- Share of RE [%]:
- $E_{PV}$ [TWh]: 0 8 16 18 26 28 36 40 50 52 58 60 66 90
- $E_{Wind}$ [TWh]: 0 40 80 100 200 250 50 200 250 50 100 200 250
15-min gradients do not increase with higher wind penetration

Standard deviation of 15-min gradients of residual load for different wind penetrations and scenarios
15-min gradients do not increase with higher wind penetration

Standard deviation of 15-min gradients of residual load for different wind penetrations and scenarios

Share of RE [%]:
- No wind energy
- Uniform
- All in one place
- High wind speed
- Minimal ramps
- Grid-focused

$\sigma (\Delta P_{15\text{min}}) \text{ [GW]}$

$E_{PV} \text{ [TWh]}:$
- 0
- 40
- 80
- 40
- 80
- 40
- 80
- 200
- 200
- 58
- 60
- 66
- 90
- 200
- 250

$E_{Wind} \text{ [TWh]}:$
- 0
- 50
- 50
- 100
- 0
- 50
- 250
- 0
- 250
- 50
- 250
- 250
Findings of analysis of short-term fluctuations

PV is the main driver for 15-minute gradients in the residual load

• This is due to the astronomical movement of the sun which causes bell-shaped output of solar PV in a clearly defined pattern every day
• These 15-minute gradients caused by solar PV exist, but are highly predictable (caused primarily by the highly predictable astronomical movement of the sun)

Adding wind energy does not increase the standard deviation of 15-min gradients

Higher overall shares of RE can be realized with low standard deviations as well but show a stronger dependency on the ratio of wind to PV

A share of up to ~30% of RE causes no significant increase in 15-minute gradients

Wind alone can provide 50% of the total energy demand without significant increase in the 15-minute gradients; the wind output changes are more low frequency over several hours
Putting wind turbines in one place makes the supply volatile

Statistics of aggregated wind output and residual load for the “all-in-one-place” wind distribution

<table>
<thead>
<tr>
<th></th>
<th>Potential</th>
<th>50 TWh/yr</th>
<th>100 TWh/yr</th>
<th>250 TWh/yr</th>
<th>All in one place 100 TWh/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Capacity</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.16 GW</td>
<td>16 GW</td>
<td>32 GW</td>
<td>81 GW</td>
<td>32 GW</td>
</tr>
<tr>
<td><strong>Minimum output</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0 GW</td>
<td>0 GW</td>
<td>0 GW</td>
<td>0 GW</td>
<td>0 GW</td>
</tr>
<tr>
<td><strong>Normalised wind power 15-min gradient</strong></td>
<td>Max</td>
<td>92%</td>
<td>92%</td>
<td>92%</td>
<td>92%</td>
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<tr>
<td></td>
<td>Min</td>
<td>-91%</td>
<td>-91%</td>
<td>-91%</td>
<td>-91%</td>
</tr>
<tr>
<td><strong>Residual load 15-min gradient</strong></td>
<td>Max</td>
<td>5.5 GW</td>
<td>15 GW</td>
<td>30 GW</td>
<td>74 GW</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>-3.1 GW</td>
<td>-15 GW</td>
<td>-30 GW</td>
<td>-74 GW</td>
</tr>
<tr>
<td><strong>Daily energy</strong></td>
<td>Max</td>
<td>3.5 GWh</td>
<td>354 GWh</td>
<td>708 GWh</td>
<td>1 769 GWh</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>1.3 GWh</td>
<td>137 GWh</td>
<td>274 GWh</td>
<td>685 GWh</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>0 GWh</td>
<td>0.5 GWh</td>
<td>1.0 GWh</td>
<td>2.5 GWh</td>
</tr>
</tbody>
</table>
A uniform wind turbine distribution reduces 15-min gradients to +/- 4% of nominal installed wind capacity

Statistics of aggregated wind output and residual load for the uniform wind turbine distribution

<table>
<thead>
<tr>
<th></th>
<th>Potential</th>
<th>50 TWh/yr</th>
<th>100 TWh/yr</th>
<th>250 TWh/yr</th>
<th>All in one place 100 TWh/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Capacity</strong></td>
<td>6 787 GW</td>
<td>16 GW</td>
<td>31 GW</td>
<td>78 GW</td>
<td>32 GW</td>
</tr>
<tr>
<td><strong>Minimum output</strong></td>
<td>162 GW</td>
<td>0.4 GW</td>
<td>0.8 GW</td>
<td>1.9 GW</td>
<td>0 GW</td>
</tr>
<tr>
<td><strong>Normalised wind power 15-min gradient</strong></td>
<td>Max</td>
<td>4.2%</td>
<td>4.2%</td>
<td>4.2%</td>
<td>4.2%</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>-4.3%</td>
<td>-4.3%</td>
<td>-4.3%</td>
<td>-4.3%</td>
</tr>
<tr>
<td><strong>Residual load 15-min gradient</strong></td>
<td>Max</td>
<td>291 GW</td>
<td>5.4 GW</td>
<td>5.3 GW</td>
<td>4.7 GW</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>-285 GW</td>
<td>-3.2 GW</td>
<td>-3.3 GW</td>
<td>-3.6 GW</td>
</tr>
<tr>
<td><strong>Daily energy</strong></td>
<td>Max</td>
<td>119 449 GWh</td>
<td>274 GWh</td>
<td>549 GWh</td>
<td>1 374 GWh</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>59 494 GWh</td>
<td>137 GWh</td>
<td>274 GWh</td>
<td>685 GWh</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>13 327 GWh</td>
<td>31 GWh</td>
<td>61 GWh</td>
<td>153 GWh</td>
</tr>
</tbody>
</table>
A uniform wind turbine distribution reduces 15-min gradients to +/- 4% of nominal installed wind capacity

Statistics of aggregated wind output and residual load for the uniform wind turbine distribution

<table>
<thead>
<tr>
<th></th>
<th>Potential</th>
<th>50 TWh/yr</th>
<th>100 TWh/yr</th>
<th>250 TWh/yr</th>
<th>All in one place 100 TWh/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity</td>
<td>6 787 GW</td>
<td>16 GW</td>
<td>31 GW</td>
<td>78 GW</td>
<td>32 GW</td>
</tr>
<tr>
<td>Minimum output</td>
<td></td>
<td>162 GW</td>
<td>0.4 GW</td>
<td>0.8 GW</td>
<td>1.9 GW</td>
</tr>
<tr>
<td>Normalised wind power 15-min gradient</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residual load 15-min gradient</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Daily energy</td>
<td>Mean</td>
<td>59 494 GWh</td>
<td>137 GWh</td>
<td>274 GWh</td>
<td>685 GWh</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>13 327 GWh</td>
<td>31 GWh</td>
<td>61 GWh</td>
<td>1 534 GWh</td>
</tr>
</tbody>
</table>

This capacity would be sufficient to cover the entire world's electricity demand of about 20 000 TWh/yr!
Putting wind turbines at high-wind-speed sites only leads to higher short-term gradients (+/- 8%) and low min output

Statistics of aggregated wind output and residual load for the “high-wind-speed” wind distribution

<table>
<thead>
<tr>
<th></th>
<th>Potential</th>
<th>50 TWh/yr</th>
<th>100 TWh/yr</th>
<th>250 TWh/yr</th>
<th>All in one place 100 TWh/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Capacity</strong></td>
<td>6 787 GW</td>
<td>15 GW</td>
<td>30 GW</td>
<td>76 GW</td>
<td>32 GW</td>
</tr>
<tr>
<td><strong>Minimum output</strong></td>
<td>162 GW</td>
<td>0.01 GW</td>
<td>0.04 GW</td>
<td>0.08 GW</td>
<td>0 GW</td>
</tr>
<tr>
<td><strong>Normalised wind power</strong></td>
<td><strong>15-min gradient</strong></td>
<td>4.2%</td>
<td>16%</td>
<td>12%</td>
<td>8.4%</td>
</tr>
<tr>
<td></td>
<td><strong>Min</strong></td>
<td>-4.3%</td>
<td>-17%</td>
<td>-12%</td>
<td>-8.5%</td>
</tr>
<tr>
<td><strong>Residual load</strong></td>
<td><strong>15-min gradients</strong></td>
<td>292 GW</td>
<td>5.4 GW</td>
<td>5.9 GW</td>
<td>9.0 GW</td>
</tr>
<tr>
<td></td>
<td><strong>Min</strong></td>
<td>-286 GW</td>
<td>-3.3 GW</td>
<td>-4.3 GW</td>
<td>-5.7 GW</td>
</tr>
<tr>
<td><strong>Daily energy</strong></td>
<td><strong>Max</strong></td>
<td>119 450 GWh</td>
<td>301 GWh</td>
<td>603 GWh</td>
<td>1 539 GWh</td>
</tr>
<tr>
<td></td>
<td><strong>Mean</strong></td>
<td>59 494 GWh</td>
<td>138 GWh</td>
<td>275 GWh</td>
<td>686 GWh</td>
</tr>
<tr>
<td></td>
<td><strong>Min</strong></td>
<td>13 327 GWh</td>
<td>2.9 GWh</td>
<td>6.7 GWh</td>
<td>15 GWh</td>
</tr>
</tbody>
</table>
## Wind turbine distribution to reduce 15-min-ramps: +/- 4%

Statistics of aggregated wind output and residual load for the “minimum gradients” wind distribution

<table>
<thead>
<tr>
<th></th>
<th>Potential</th>
<th>50 TWh/yr</th>
<th>100 TWh/yr</th>
<th>250 TWh/yr</th>
<th>All in one place 100 TWh/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Capacity</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6 787 GW</td>
<td>17 GW</td>
<td>33 GW</td>
<td>82 GW</td>
<td>32 GW</td>
</tr>
<tr>
<td><strong>Minimum output</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>162 GW</td>
<td>0.04 GW</td>
<td>0.16 GW</td>
<td>2.5 GW</td>
<td>0 GW</td>
</tr>
<tr>
<td><strong>Normalised wind power 15-min gradient</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max</td>
<td></td>
<td>4.2%</td>
<td>10%</td>
<td>7.7%</td>
<td>4.5%</td>
</tr>
<tr>
<td>Min</td>
<td></td>
<td>-4.3%</td>
<td>-7.2%</td>
<td>-4.6%</td>
<td>-3.8%</td>
</tr>
<tr>
<td><strong>Residual load 15-min gradient</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max</td>
<td></td>
<td>292 GW</td>
<td>5.2 GW</td>
<td>5.0 GW</td>
<td>4.6 GW</td>
</tr>
<tr>
<td>Min</td>
<td></td>
<td>-286 GW</td>
<td>-3.0 GW</td>
<td>-4.9 GW</td>
<td>-1.3 GW</td>
</tr>
<tr>
<td><strong>Daily energy</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max</td>
<td></td>
<td>119 450 GWh</td>
<td>265 GWh</td>
<td>499 GWh</td>
<td>1 198 GWh</td>
</tr>
<tr>
<td>Mean</td>
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<td>59 494 GWh</td>
<td>137 GWh</td>
<td>274 GWh</td>
<td>685 GWh</td>
</tr>
<tr>
<td>Min</td>
<td></td>
<td>13 327 GWh</td>
<td>32 GWh</td>
<td>84 GWh</td>
<td>247 GWh</td>
</tr>
</tbody>
</table>

---

Additional pixel for 100 TWh wind power

Additional pixel for 250 TWh wind power
South Africa is split into 27 supply areas – midpoints of these areas are used to measure distance and wind correlation.
The further two wind farms are away from each other, the lower the correlation between their power-production profiles.

Correlation of wind-power production between supply areas

![Graph showing correlation coefficient between wind power feed-ins of supply areas vs. distance between centres of supply areas. The graph includes a logarithmic fit equation: \(-0.246 \ln(d) + 1.9558\).]
Correlation of wind-power gradients is low for far distances

Correlation of 15-min and 1-hr gradients of wind-power production between supply areas

15 minutes gradients

1 hour gradients
Very high wind penetration (250 wind at 500 TWh/yr load): at times, electricity surpluses will occur (negative residual load)
The total amount of energy during periods of excess electricity gives an indication for bulk storage needs

- Electricity deficit can be provided by conventional or flexible power fleet
- Electricity surplus can either be curtailed or stored
- Longest period of continuous excess generation: 18-60 hours, depending on the spatial distribution of the wind fleet

Load: 500 TWh/yr
Wind: 250 TWh/yr
PV: 80 TWh/yr

Cumulated electricity surplus (from negative residual load)
Cumulated electricity deficit (from positive residual load)
Depending on the scenario, between 18-72 hours of continuous excess electricity can occur.

Electricity surpluses: Maximum duration by scenario.
Excess energy is mainly caused by high solar PV shares
Generated solar PV and wind energy and split into useful and excess for different VRE penetrations

- **Low PV / low wind**
  - Load: 500 TWh/yr
  - PV: 40 TWh/yr
  - Wind: 50 TWh/yr

- **Medium PV / low wind**
  - Load: 500 TWh/yr
  - PV: 80 TWh/yr
  - Wind: 50 TWh/yr

- **High PV / low wind**
  - Load: 500 TWh/yr
  - PV: 200 TWh/yr
  - Wind: 50 TWh/yr

<table>
<thead>
<tr>
<th>Load</th>
<th>Solar PV (TWh/yr)</th>
<th>Wind (TWh/yr)</th>
<th>Residual Load (TWh/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low PV / low wind</td>
<td>500</td>
<td>40</td>
<td>50</td>
</tr>
<tr>
<td>Medium PV / low wind</td>
<td>500</td>
<td>80</td>
<td>50</td>
</tr>
<tr>
<td>High PV / low wind</td>
<td>500</td>
<td>200</td>
<td>50</td>
</tr>
</tbody>
</table>

**Share of useful VRE in total system load**

- **Low PV / low wind**: 18%
- **Medium PV / low wind**: 26%
- **High PV / low wind**: 44%
2x wind (50 to 100 TWh/yr): almost no effect on excess energy
Generated solar PV and wind energy and split into useful and excess for different VRE penetrations

Low PV / medium wind
Load: 500 TWh/yr
PV: 40 TWh/yr
Wind: 100 TWh/yr

Medium PV / medium wind
Load: 500 TWh/yr
PV: 80 TWh/yr
Wind: 100 TWh/yr

High PV / medium wind
Load: 500 TWh/yr
PV: 200 TWh/yr
Wind: 100 TWh/yr

TWh/yr
System Load Solar PV Wind Residual Load
500 40 100 360
28%

TWh/yr
System Load Solar PV Wind Residual Load
500 80 100 320
36%

TWh/yr
System Load Solar PV Wind Residual Load
500 200 100 340
52%

Share of useful VRE in total system load
Excess PV/wind Wind Solar PV

xx%
65% VRE share achievable with almost no excess energy
Generated solar PV and wind energy and split into useful and excess for different VRE penetrations

Low PV / high wind
Load: 500 TWh/yr
PV: 40 TWh/yr
Wind: 250 TWh/yr

Medium PV / high wind
Load: 500 TWh/yr
PV: 80 TWh/yr
Wind: 250 TWh/yr

High PV / high wind
Load: 500 TWh/yr
PV: 200 TWh/yr
Wind: 250 TWh/yr

TWh/yr

System Load | Solar PV | Wind | Residual Load
---------- | ------- | ---- | ---------------
Low PV / high wind |
500 | 40 | 250 | 1

System Load | Solar PV | Wind | Residual Load
Medium PV / high wind |
500 | 80 | 250 | 3

System Load | Solar PV | Wind | Residual Load
High PV / high wind |
500 | 200 | 250 | 125

58% | 65% | 75%

Excess PV/wind | Wind | Solar PV
--- | --- | ---

Share of useful VRE in total system load
Electricity surpluses: 65% energy share of solar PV/wind does not cause significant excess electricity

Electricity storage to absorb excess electricity is only required at very high shares of VRE

Excess electricity at very high shares of VRE is mainly driven by solar PV

- Up to a certain energy share, solar PV does not cause excess electricity
- Beyond a threshold, solar PV causes large amounts of excess electricity because of the skewed supply pattern of solar PV (daytime only)
- Wind supply is more volatile, but on average better distributed over the full 24 hours of the day
- Very high shares of wind energy can be achieved without any significant amounts of excess electricity (assuming the wind farms are distributed widely across the country)

For example for 65% VRE share (80 TWh PV and 250 TWh wind, grid-focused distribution, 500 TWh/yr system load), excess electricity is only 1.2% of total solar PV/wind energy produced

Side note: in the 65% VRE case, the entire residual load’s fluctuations can be balanced by a conventional fleet that has a fuel-storage capacity of 48 days of the average power output (Eskom currently stocks coal on average for the entire fleet for 57 days)
Uniform distribution of wind turbines leads to ~85% lower forecast error for intra-day and ~60% lower for day-ahead.

Years considered: 2009-2013
Methodology to derive relative LCOE per pixel

Relative wind farm cost
Turbine type 5 is approximately
25% more expensive than turbine type 1

Capex: 80% of overall costs
→ LCOE of turbine type 5 is approximately 20%
higher than turbine type 1 (for the same load factor)

Map of relative LCOE (for the same load factor)

Reference pixel
Turbine 1, load factor ~30%

For every pixel: determine load factor multiplier

Relative LCOE by multiplying costs with
scaled load factors
Large parts of RSA can achieve LCOE well below reference

Relative LCOE across South Africa when installing turbine types 1 to 5

Reference pixel (turbine type 1, ~30% load factor)
Large parts of RSA can achieve LCOE well below reference

Relative LCOE across South Africa when installing turbine types 1 to 3 only (i.e. type 3 at 4/5 pixels)
Large parts of the South African suitable land (entire land mass less exclusion zones) can achieve low wind LCOEs

A relative LCOE of 90% or less can be achieved at 44% of the South African land mass (less exclusion zones); 100% benchmark is a high-wind-speed pixel
Results of the aggregation study

South Africa exhibits extremely good conditions for both wind and solar energy

• Almost the entire country has sufficient resources for profitable wind projects
• High load factors can be achieved almost everywhere (both for solar PV and wind)

South Africa has more than enough space

• It is possible to generate much more electricity from wind and solar energy than what is needed (solar PV and wind potential is much higher than total demand – today and in future)

Spatial aggregation brings huge benefits and leverages South Africa’s vast land mass

• Aggregation effects: forecast error is reduced significantly for wide wind turbine distribution
• Up to 30% energy share of variable renewable energy (VRE) will not increase short-term ramps in the system significantly if there is a balanced combination of wind & PV in the system
• 50% of wind energy share alone does not significantly increase the 15-minute ramps
• The more distributed wind turbines are being installed, the stronger the aggregation effects (better possibilities of reducing fluctuations)
Contents

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5. Results
   I. Case Study Supply Area Port Elizabeth
   II. Aggregation Study
   III. Case Study Curtailment

6. Conclusions and Outlook
Curtailment analysis conducted for transmission substations

Each transmission substation has a certain rated capacity in MW (maximum evacuation)

Each solar PV/wind project has a certain rated/nominal capacity in MW (maximum output)

Status quo: solar PV/wind projects can connect to a certain substation up to the point that the sum of the rated solar PV/wind capacity equals the rated capacity of the substation

Solar PV and wind projects’ power output however is generally not highly correlated

This means that the sum of rated solar PV and wind capacity at a substation could be higher than the rated capacity of the substation without running into excess power situation often

This effect was analysed and the potential over-installation capacity of solar PV and wind was quantified for all substations across South Africa
Overcapacity of wind/solar at substation leads to curtailment
Explanation of logic of curtailment at the example of a substation with high simulated solar/wind
20% additional solar/wind can be installed without curtailment

Statistical analysis of required annual curtailment across all substations (simulating only wind/PV)
60-70% additional solar/wind can be installed per substation without curtailment if generic load is assumed

Statistical analysis of required annual curtailment across all substations (simulating wind/PV/load)

Year: 2010 to 2012, demand considered

Average
Percentage of substations [%]

1
2.5
5
10
25
50
100

Curtailed energy as share of uncurtailed annual RE feed-in [%]

Installed RE capacity as percentage of transformers capacity [%]
Curtailment analysis: Results

<table>
<thead>
<tr>
<th>Only Feed-in</th>
<th>Curtailed annual energy per total solar/PV energy</th>
<th>Minimum installable solar/wind power per substation capacity</th>
<th>Average installable solar/wind power per substation capacity</th>
<th>Maximum installable solar/wind power per substation capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>120%</td>
<td>120%</td>
<td>140%</td>
<td>140%</td>
</tr>
<tr>
<td>5%</td>
<td>140%</td>
<td>130%</td>
<td>180%</td>
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<tr>
<th>Feed-in and load (residual load)</th>
<th>Curtailed annual energy per total solar/PV energy</th>
<th>Minimum installable solar/wind power per substation capacity</th>
<th>Average installable solar/wind power per substation capacity</th>
<th>Maximum installable solar/wind power per substation capacity</th>
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<td>210%</td>
<td>240%</td>
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</tbody>
</table>
Contents

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Conclusions for South Africa

- More than 80% of South Africa's land mass has enough wind for high load factors (>30%)
- The magnitude and cost competitiveness of wind power in South Africa is on par with solar PV
- REDZ are a good starting point. When expanding the REDZ further, the wind resource should not be the limiting factor but only environmental considerations
- Short term fluctuations in the aggregated wind power feed-in are significantly reduced by wide spatial distribution
- A share of 50% wind energy in South Africa’s electricity supply does not increase the short term gradients if the wind fleet is widely distributed
- Low seasonality of wind and solar PV makes integration easier (no seasonal storage required)
- Distributing wind turbines widely leads to a forecast error improvement of ~85 % for intra-day and of ~60 % for day-ahead compared to putting all wind turbines in one place
- At least 20% additional wind/PV power can be installed per substation without any curtailment of wind/PV power (40% with 5% curtailment) – no load considered, thus conservative
Conclusions for South Africa

South Africa has perfect conditions to introduce a very large amount of variable renewables into the electricity system

• Solar and wind energy are very low-cost bulk energy providers in South Africa
• Very low seasonality of both solar and wind supply
• Very wide spread interconnected electricity system that enables spatial aggregation
• South Africa is a very large area country with low population density: space is not a constraint
Outlook

Further research is required that builds on the results achieved in this study

• Creation of virtual power plant platforms to balance variable renewables
• Develop forecast model for solar PV and wind feed-in for South Africa
• Develop the concept for reserve provision from variable renewables
• Determine the optimal mix of solar PV and wind for South Africa

Sector links: South Africa can invest into Power-to-Liquid to make the competitive advantage solar/wind resources an export article for a global CO$_2$-neutral-fuels markets

Extension of the study to the Southern African Power Pool

Data and results will be made publically available
Fraunhofer team

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Skills exchange

7 guests from South Africa in Germany in August 2015

**Topics**
- Collaborative project work
- Workshops:
  - WindPRO course
  - Micro-scale wind modelling workshop
- Presentation of a virtual power plant
- Excursions:
  - 200 m met mast
  - Wind farm
Thank you

Ke a leboha

Ke a leboga

Dankie

Ndi a livhuha

Ngiyathokoza

Ngiyabonga

ndza Khensa

Enkosi