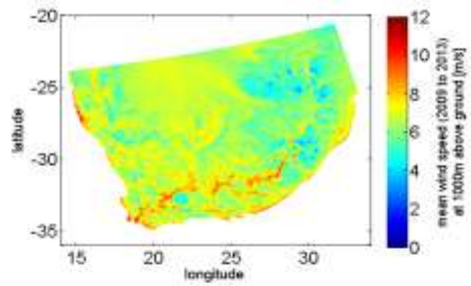
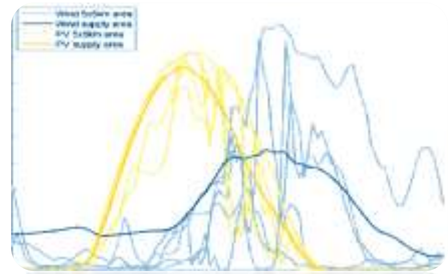
Wind and Solar PV Resource Aggregation Study for South Africa

Public presentation of results





Pretoria, 3 March 2016

Dr. Stefan Bofinger, Britta Zimmermann, Ann-Katrin Gerlach – Fraunhofer IWES
Dr. Tobias Bischof-Niemz, Crescent Mushwana – CSIR

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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

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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

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Agenda

1. **Introduction**
2. Data
3. Methodology
4. Scenarios
5. Results
6. Conclusions and Outlook

Agenda

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

Fraunhofer Institute for Wind Energy and Energy System Technology (Fraunhofer IWES)

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

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Fraunhofer IWES
Energy System Technology, Kassel

R&D for the success of the German „Energiewende“ and the global use of renewable energy








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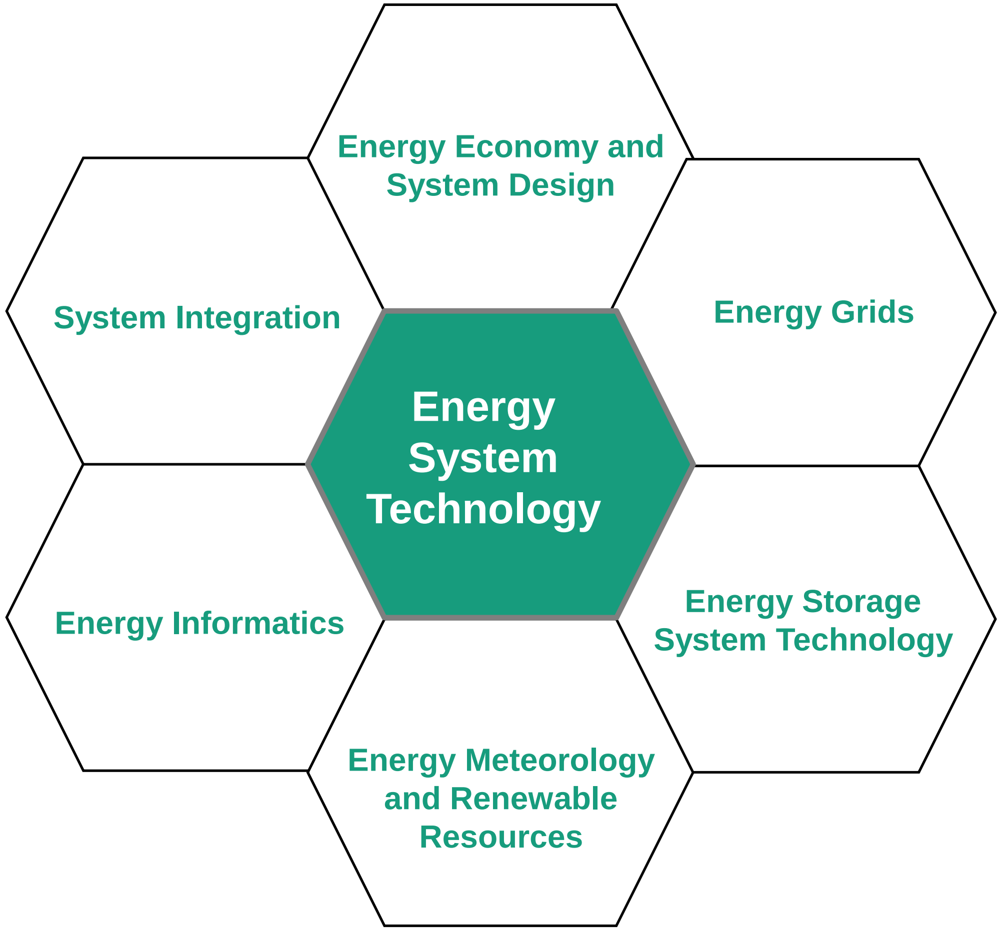
Core Skills for Energy System Technology



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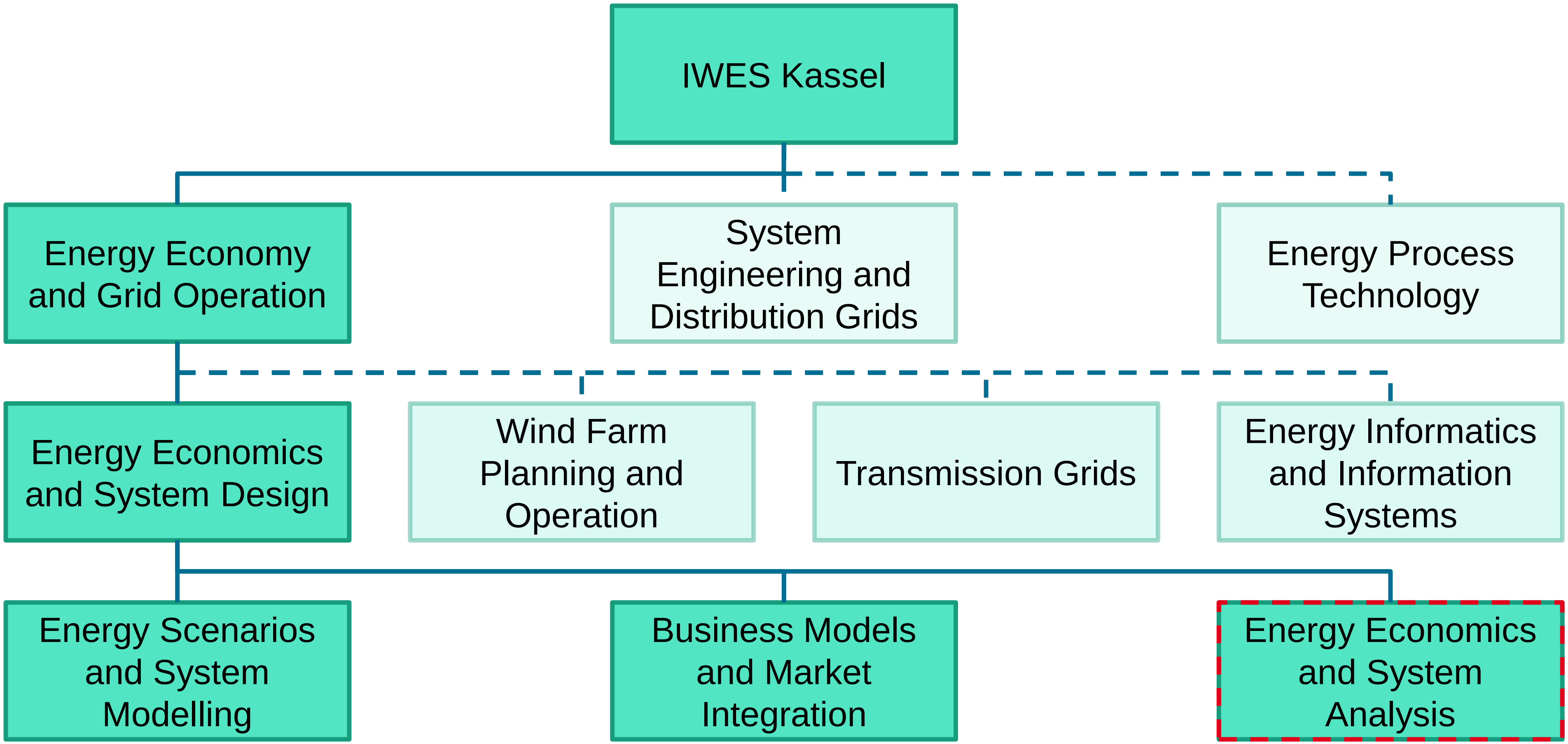
Introduction IWES – Kassel Site: Energy System Technology



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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

Rainer Schwinn

- Forecast

Jan Dobschinski

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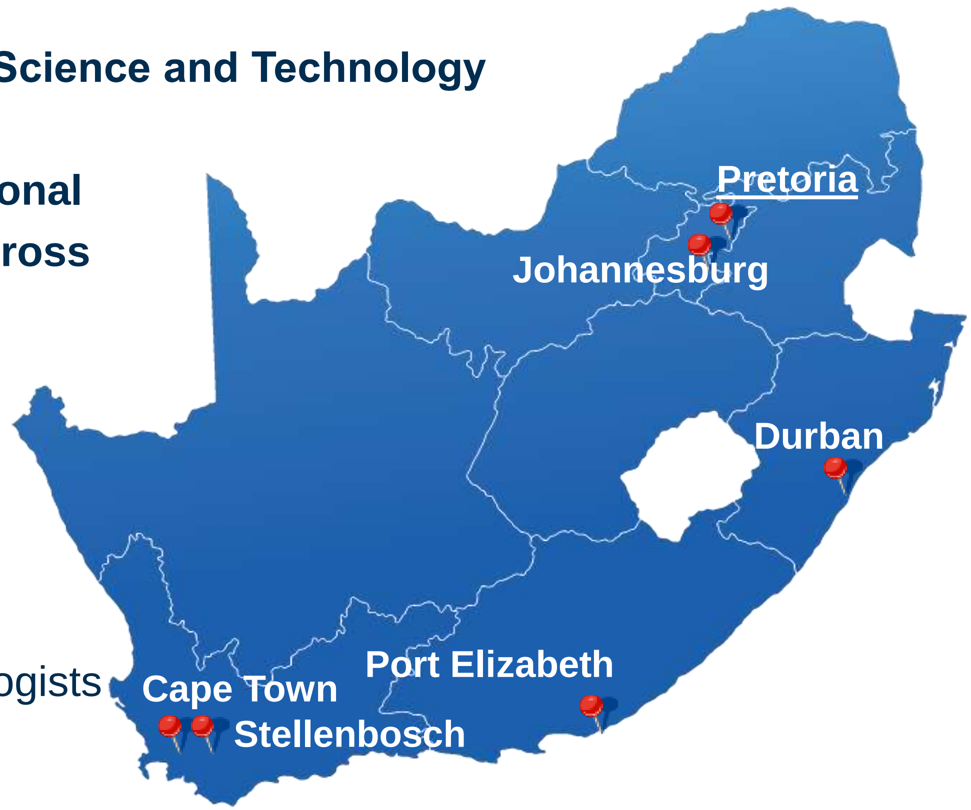
South Africa's Council for Scientific and Industrial Research (CSIR)

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)

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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

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CSIR's new Energy Centre streamlines and expands CSIR's energy research offerings in five areas – today: 20 staff members, growing

Potentially 6th area: Industry Business Cases

CSIR Energy Centre research areas

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

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

CSIR our future through science

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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
our future through science

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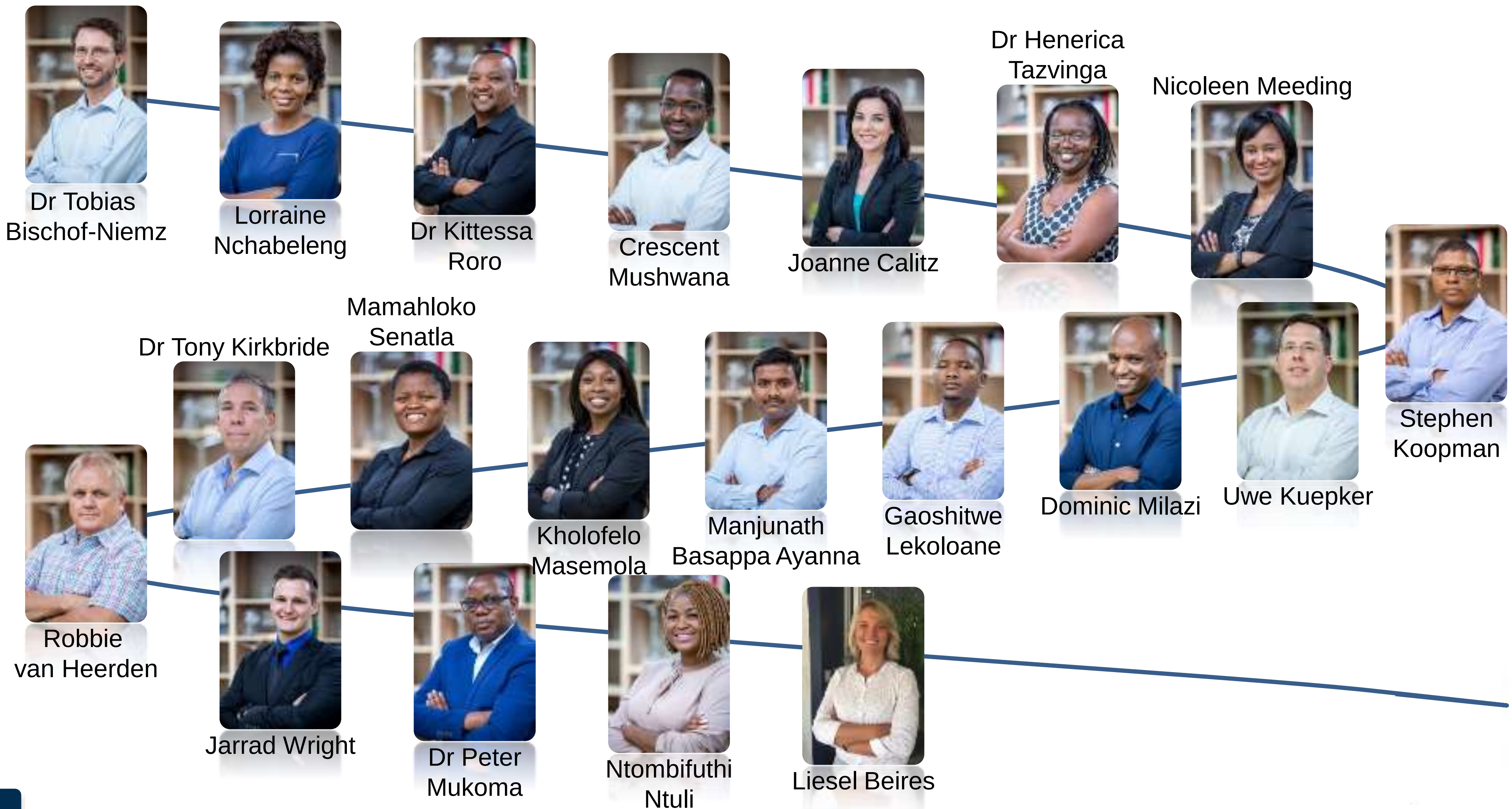
CSIR Energy Centre team as of 7 March 2016



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Sources: CSIR Energy Centre analysis

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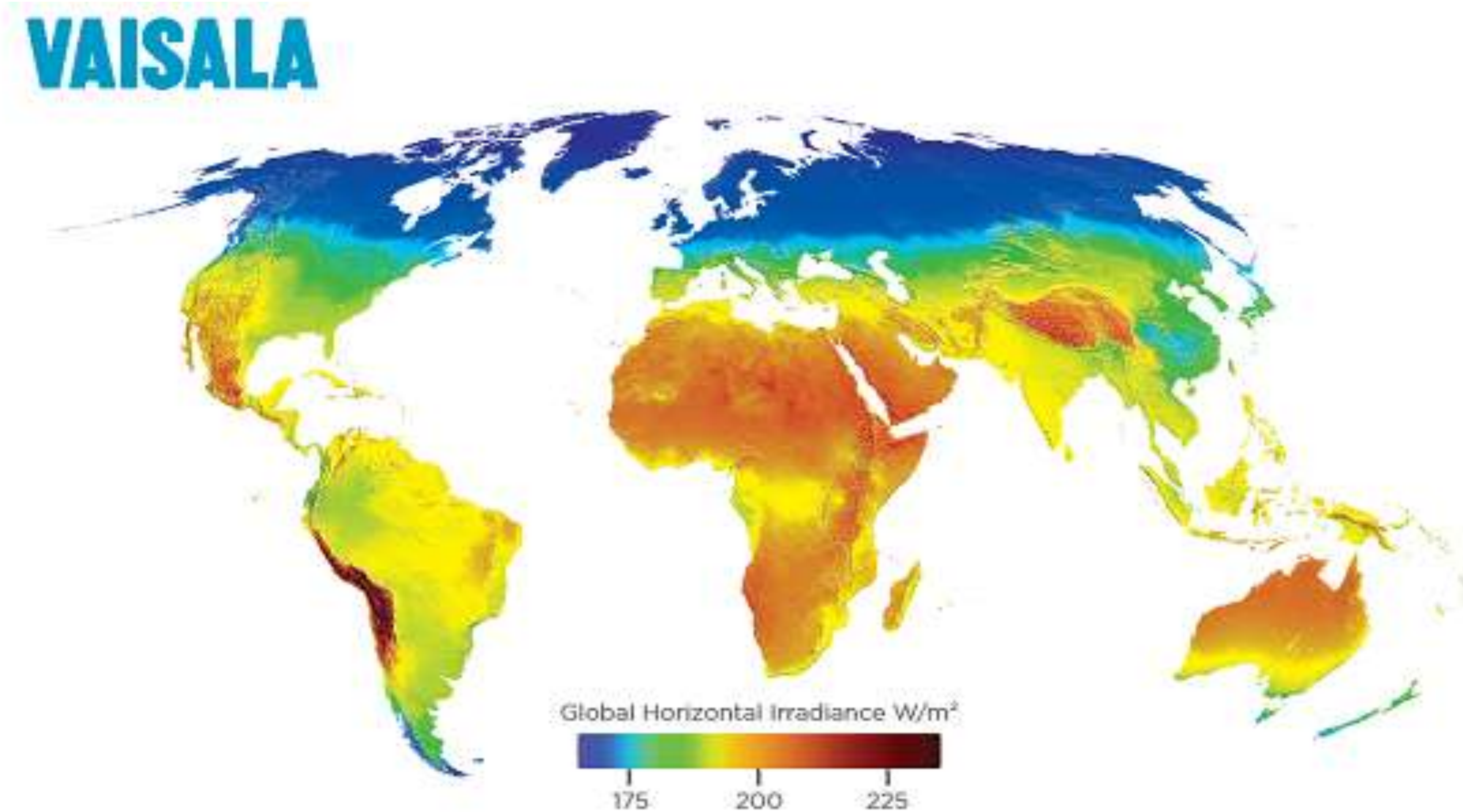
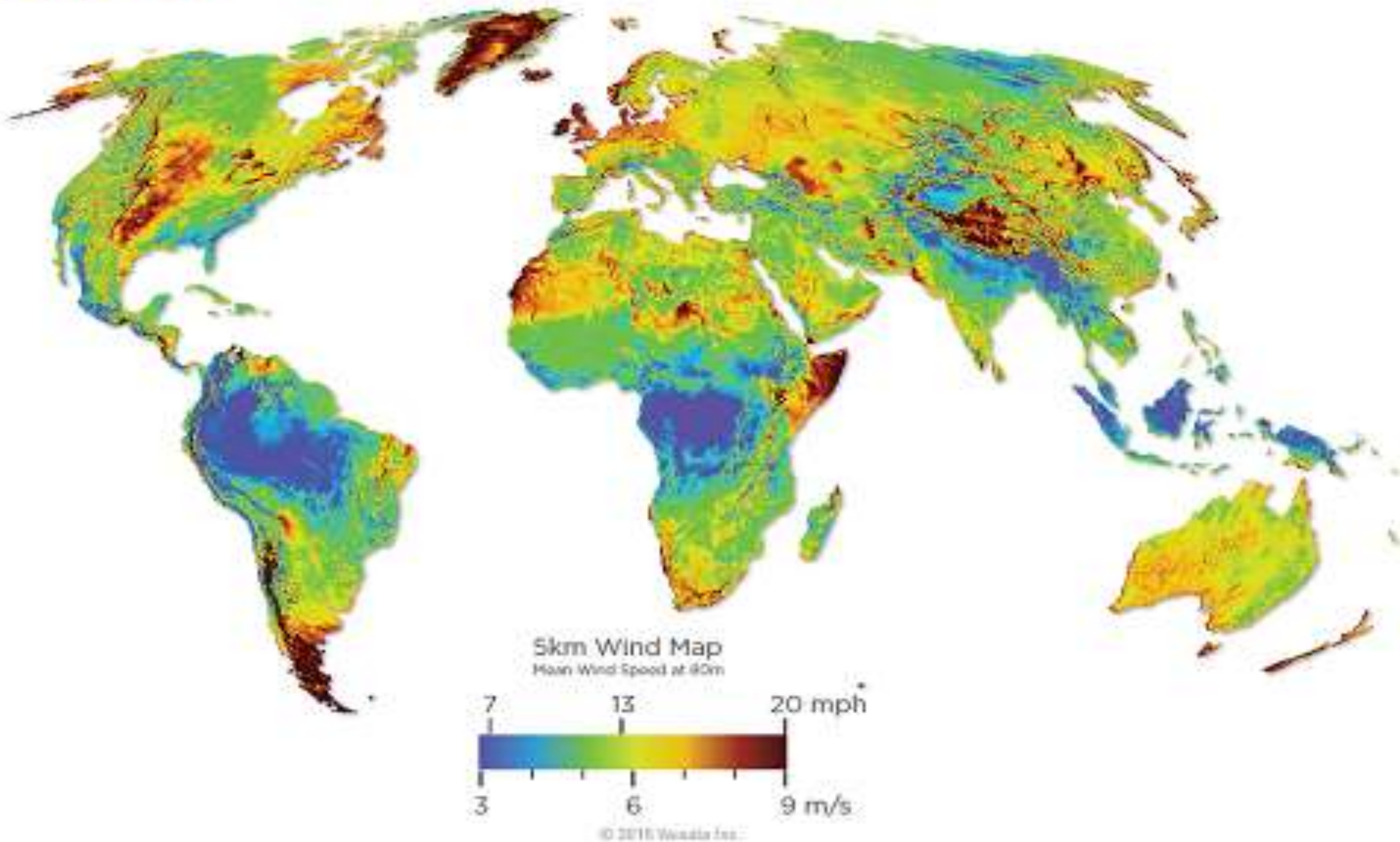
Africa has some of the best solar resources worldwide



REV 1

Southern Africa also has some of the best wind resources

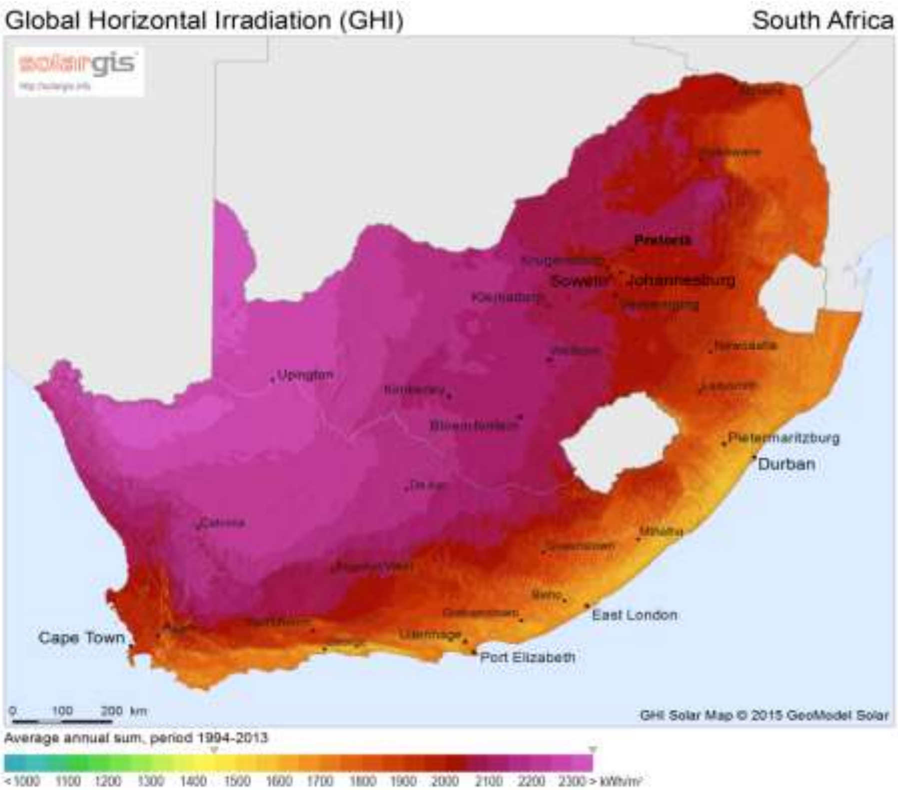
VAISALA



REV 1

South Africa has almost two times the solar resource of Germany, where solar PV is close to cost competitiveness

Solar resource in South Africa…



SA's planned PV capacity by 2030: 8.4 GW

… as compared to Germany

Germany's status today: almost 40 GW installed solar PV capacity (roughly one Eskom)

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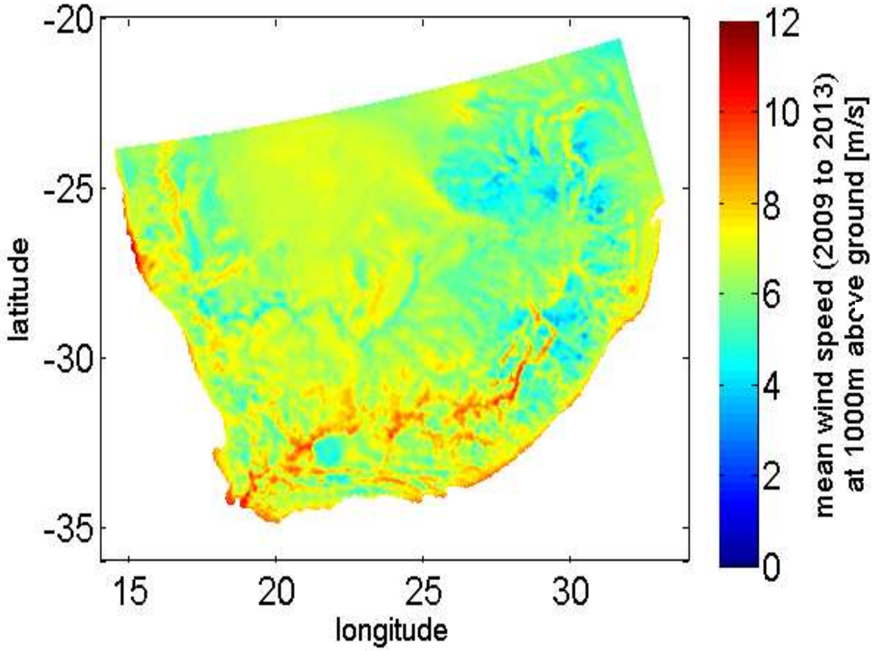
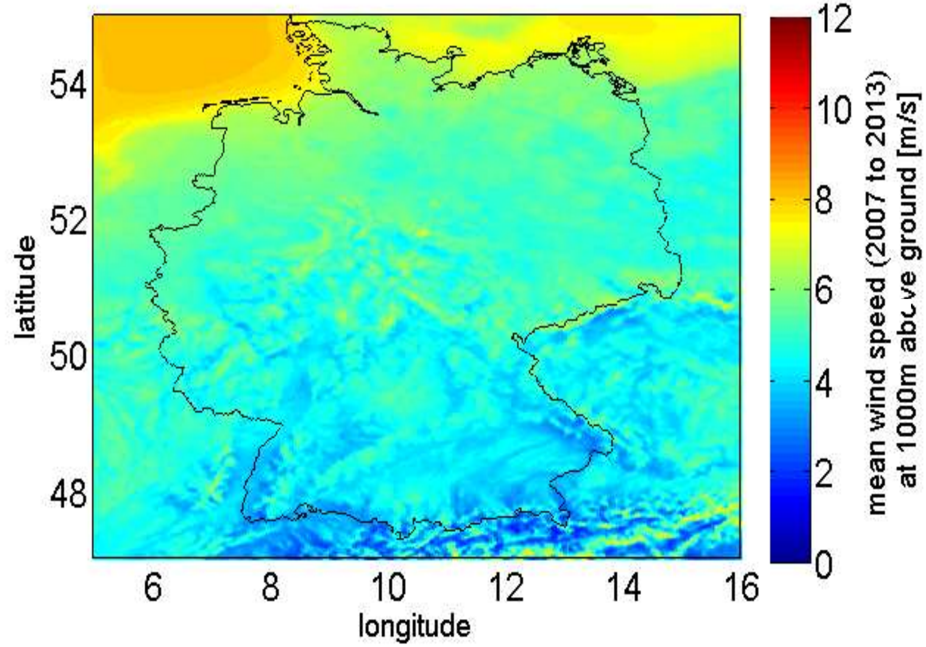
Best wind sites in Germany along the coastline have similar wind speeds as large parts of inland South Africa (yellow)

Wind resource in South Africa…



SA's planned wind capacity by 2030: 9.2 GW

… as compared to Germany



Germany's status today: almost 46 GW installed wind capacity (roughly one Eskom)

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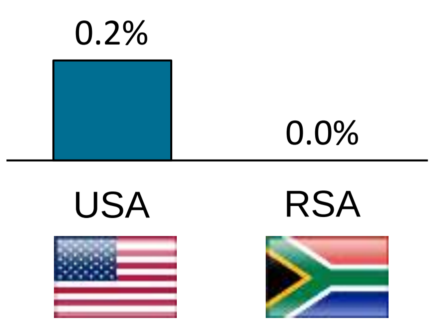
In less than two years, South African PV has outpaced the US

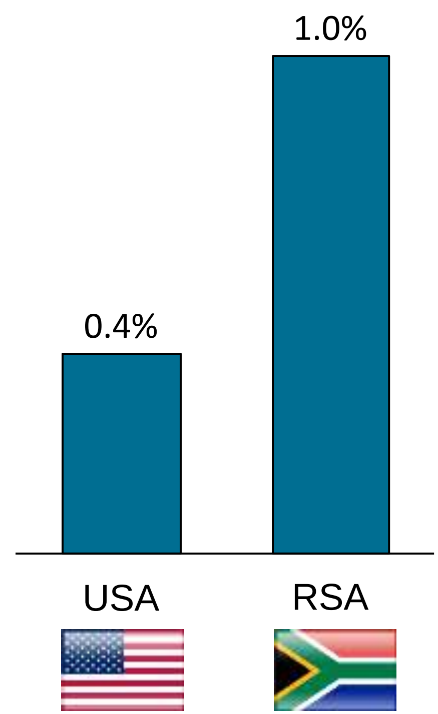
2013

Share of solar PV in electricity production



2015

Share of solar PV in electricity production



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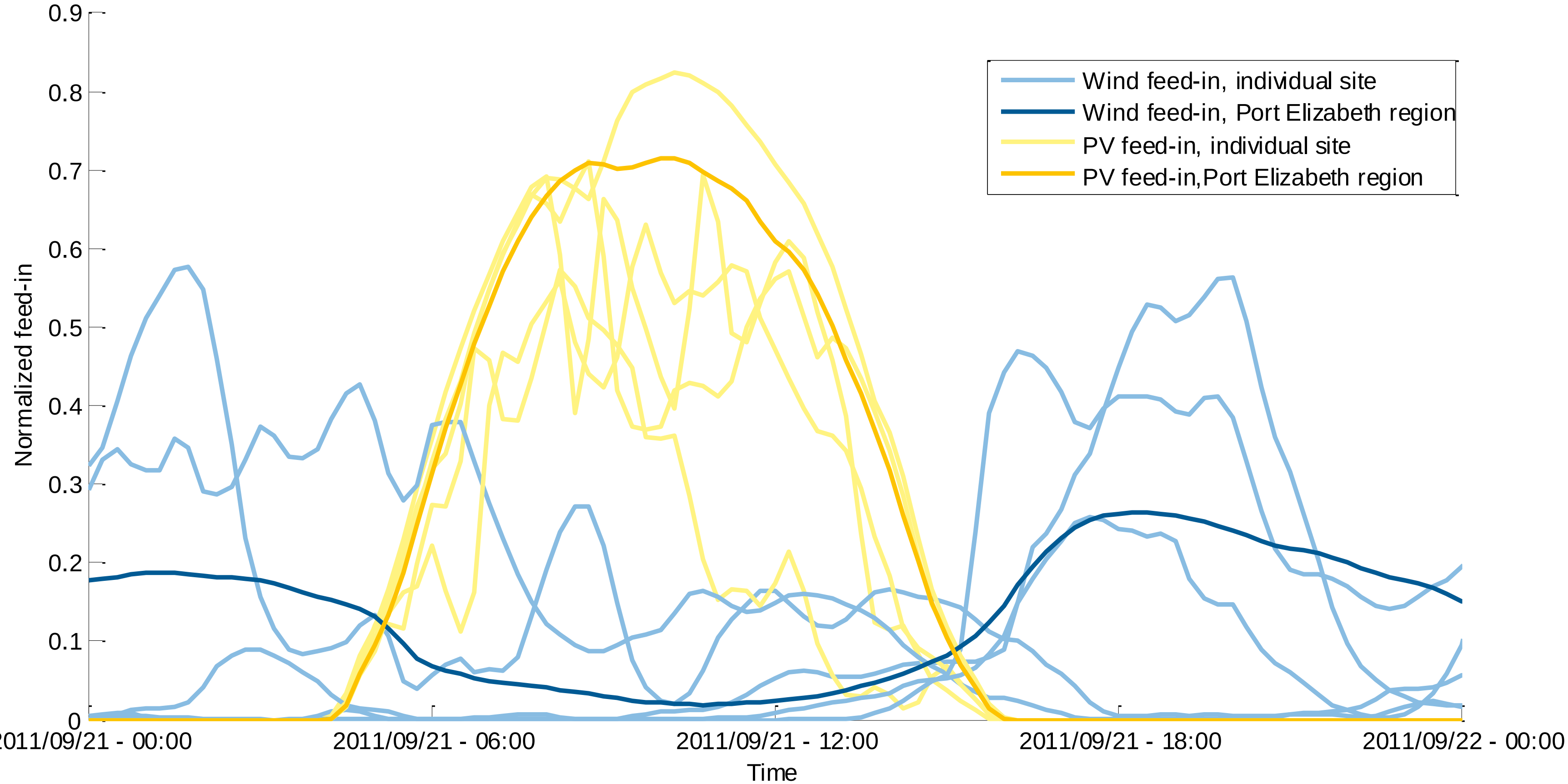
Sources: EIA; CSIR

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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Contents

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

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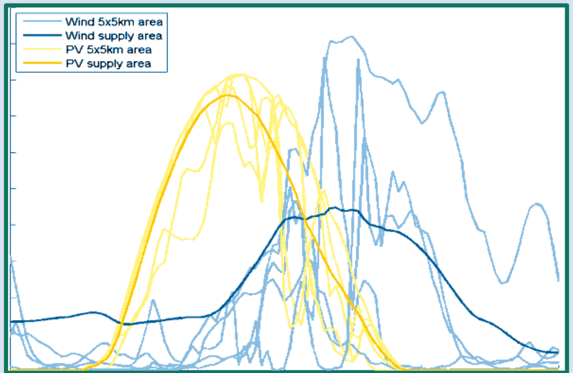
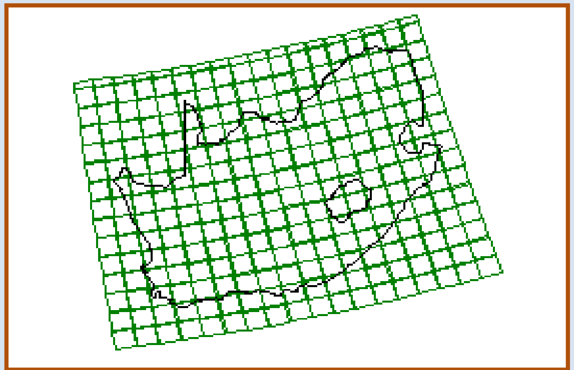
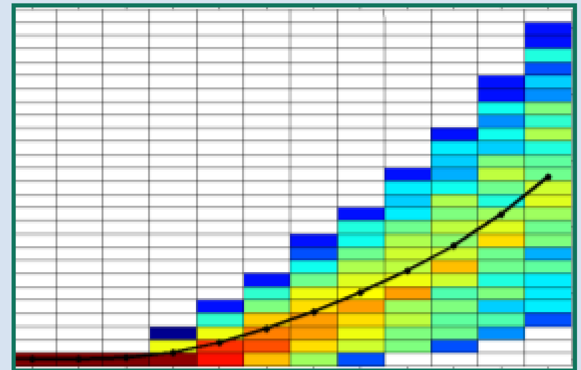
Side Tasks



Supply area

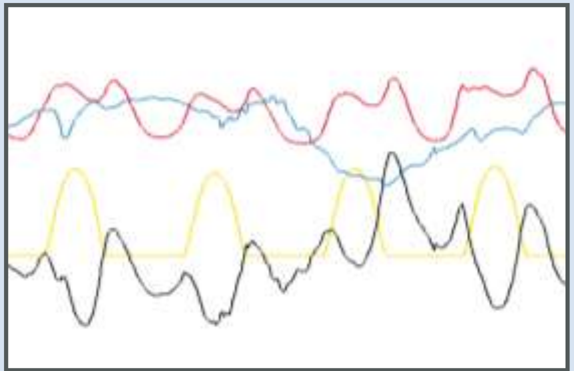


Sufficiency analysis



Curtailment analysis

WIND AND SOLAR AGGREGATION STUDY SOUTH AFRICA

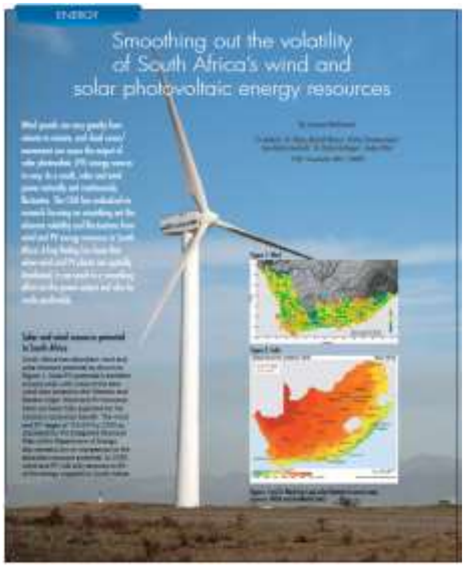


Data for IRP, ESKOM, GIZ

Skills exchange

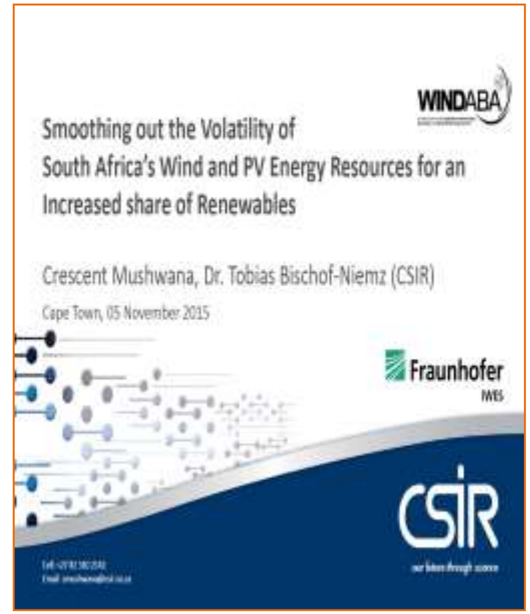
Publications issued during the course of the study

ScienceScope
PUBLICATION OF THE CSIR | VOLUME 8 | NUMBER 2 OF 2015
SOUTH AFRICA'S COUNCIL FOR SCIENTIFIC AND INDUSTRIAL RESEARCH



SAIREC 2015
South African International Renewable Energy Conference

WINDABA
An official event of the South African Wind Energy Association and Global Wind Energy Council



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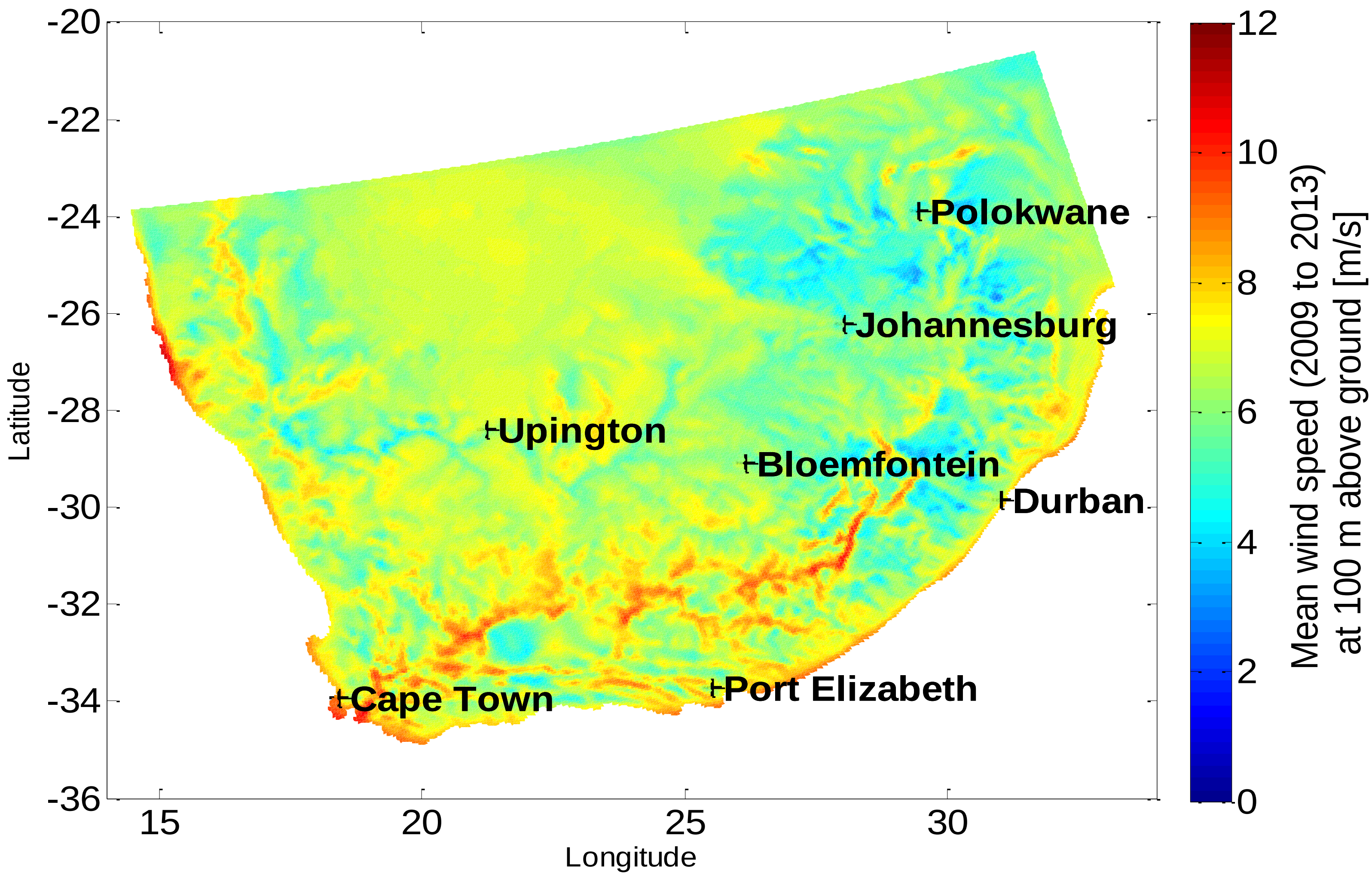
Contents

Raw data: time- and spatially synchronous wind and solar data produced from reliable raw-data sources (WASA&SODA)

Model name	WASA	SODA
Variables	Wind speed, temperature	Solar irradiation
Height	50 m, 80 m, 100 m, 150 m (v) 2 m (T)	-
Temporal coverage	2009 to 2013	2010 to 2012
Temporal resolution	15 min	15 min
Spatial coverage	South Africa	South Africa
Spatial resolution	5 km x 5 km	0.2° x 0.2° (similar to 5 km x 5 km)

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



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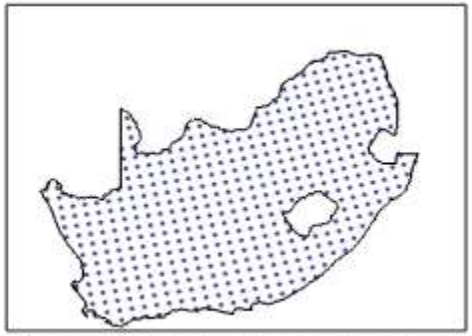
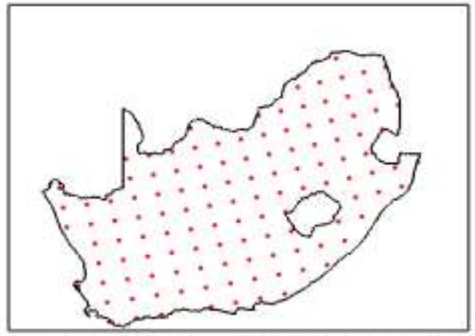
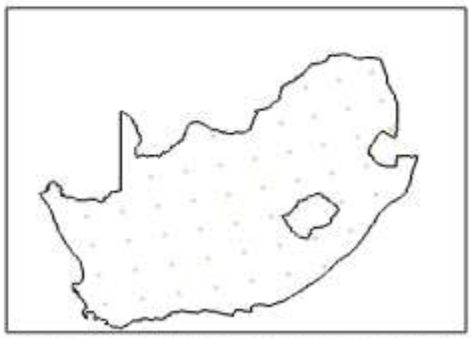
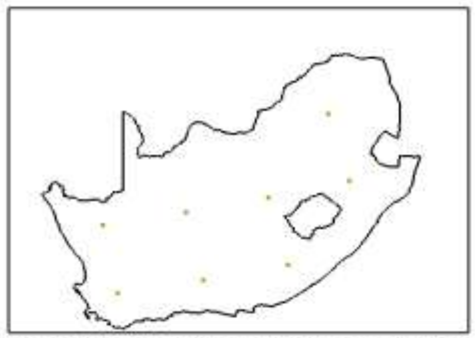
Validation: Is a 5x5 km² resolution of weather data sufficiently high for the purposes of this aggregation study?


approximate pixel distance: 50km


approximate pixel distance: 100km


approximate pixel distance: 150km


approximate pixel distance: 350km

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

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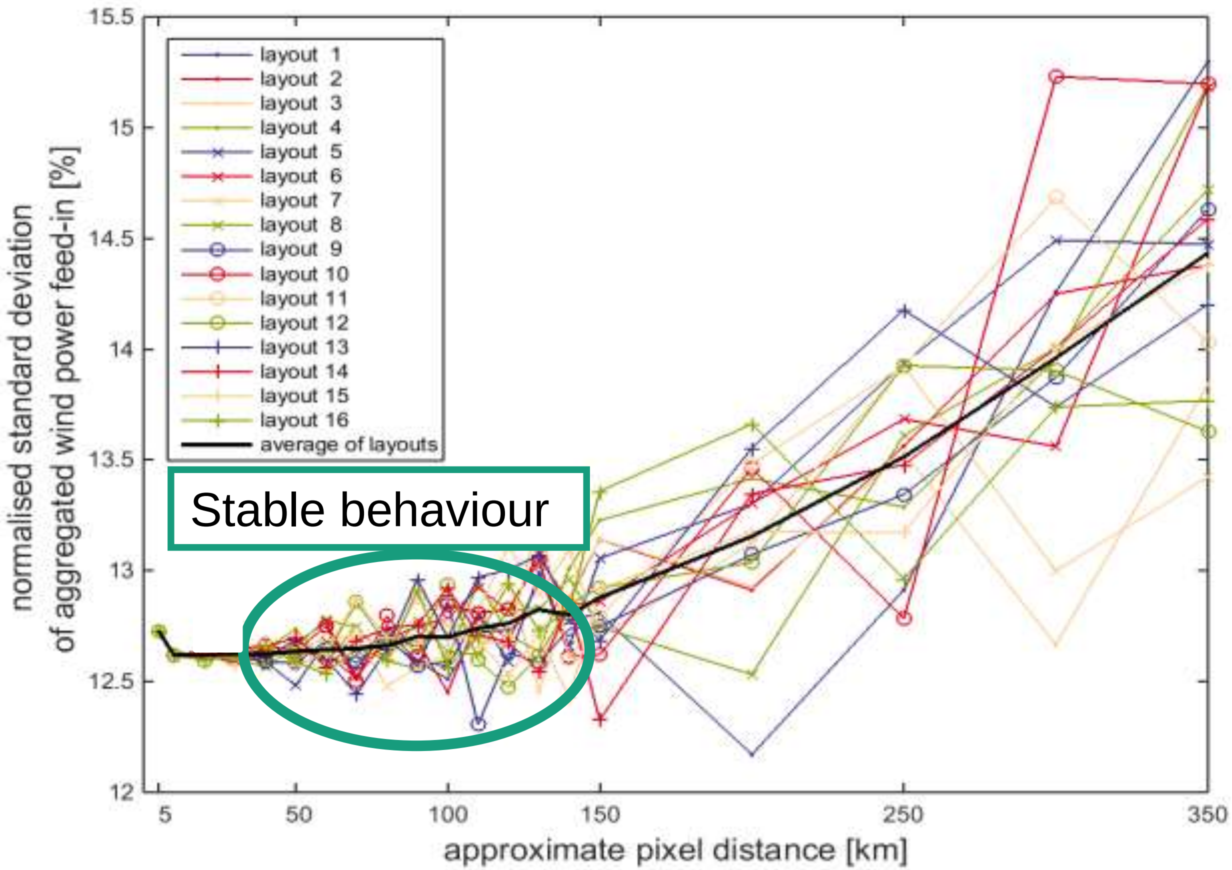
Fluctuations of aggregated wind power stay constant below 50 km pixel distance → resolution of 5x5 km high enough



Results for different starting pixels

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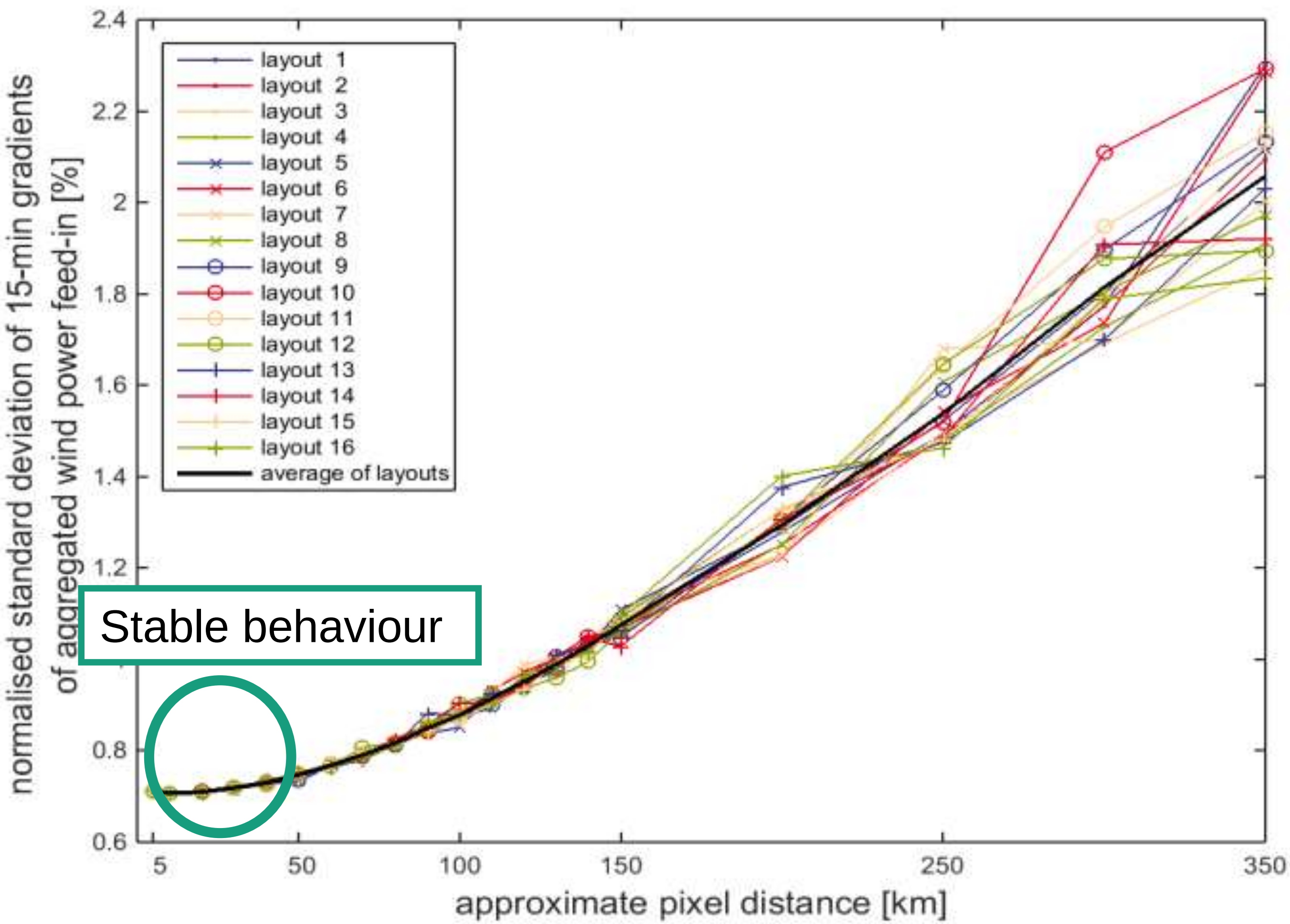
Fluctuations of 15-min ramps of aggregated wind power stay constant below 20 km pixel distance → 5x5 km sufficient



- 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

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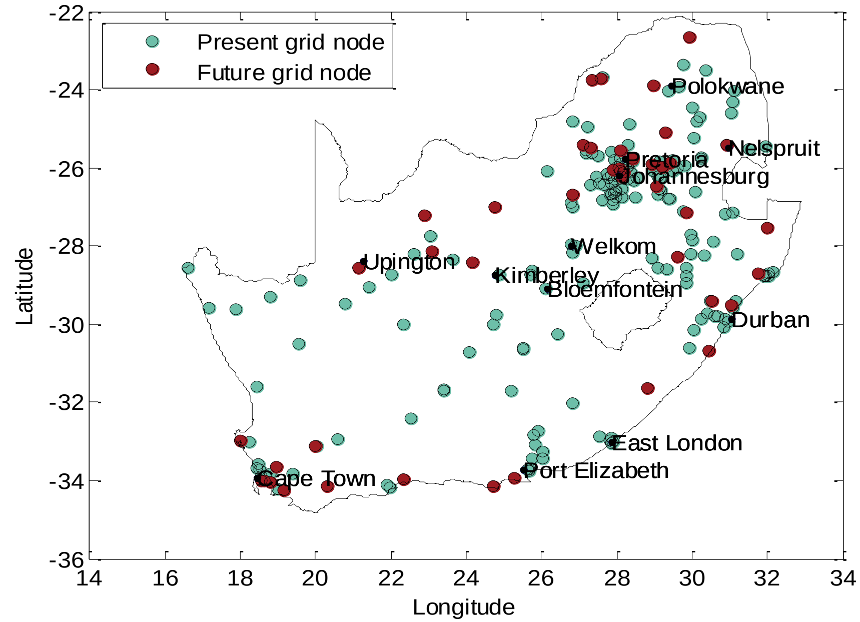
Demand: Historical spatially available load data scaled to match estimated future country demand of 500 TWh/yr

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

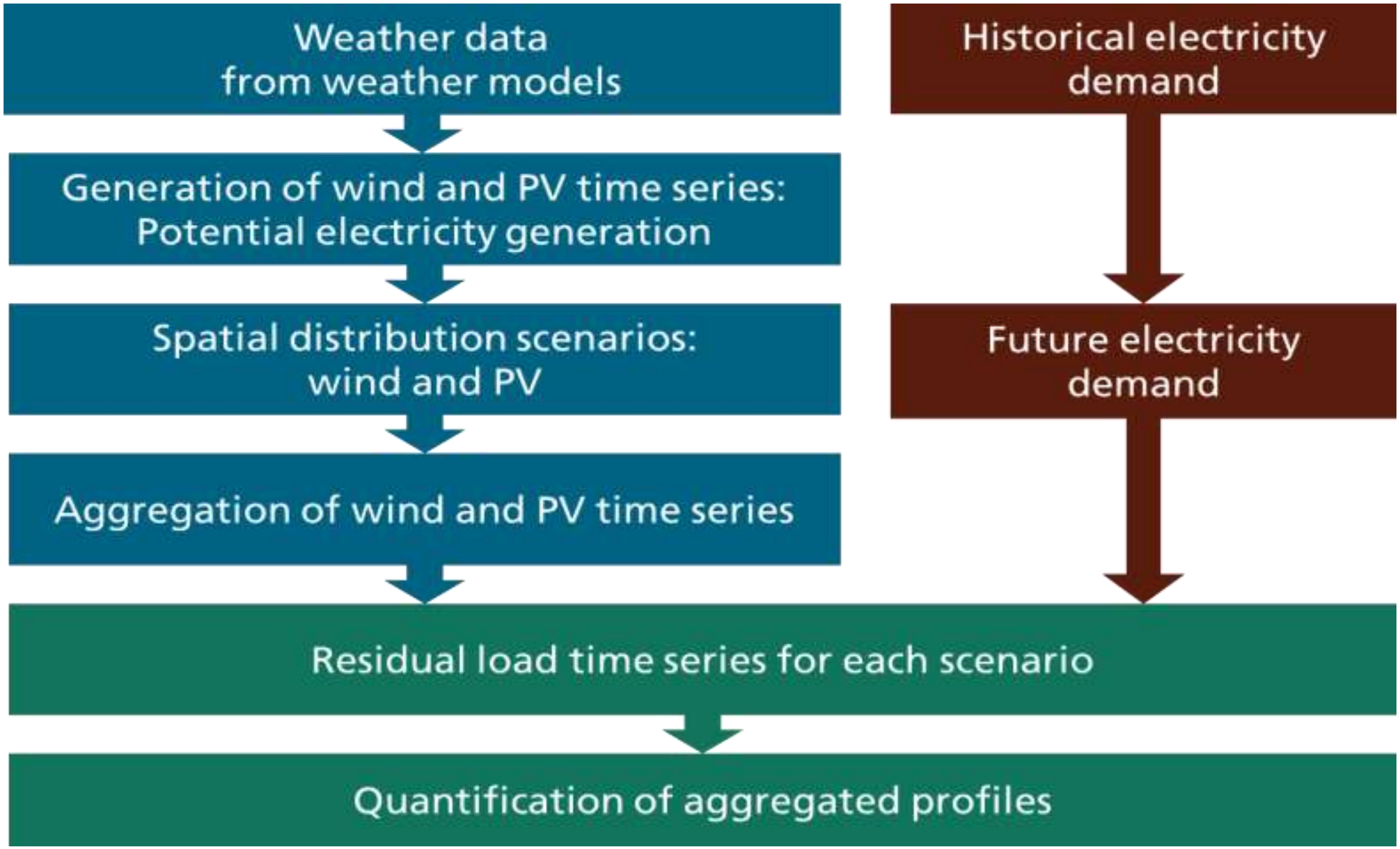
→ **Scaled on demand of single grid Nodes and allocated to grid nodes**



REV 1

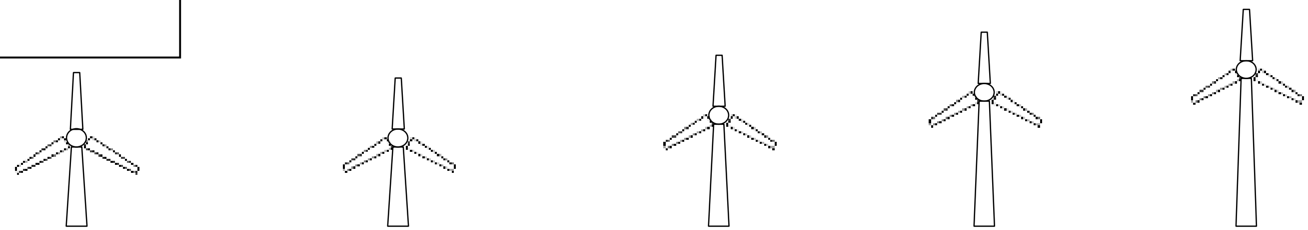
Contents

Core study approach:
Simulated wind/PV and historical load jointly analysed



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

Space requirement 0.1 km²/MW
→ max. 250 MW per pixel



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

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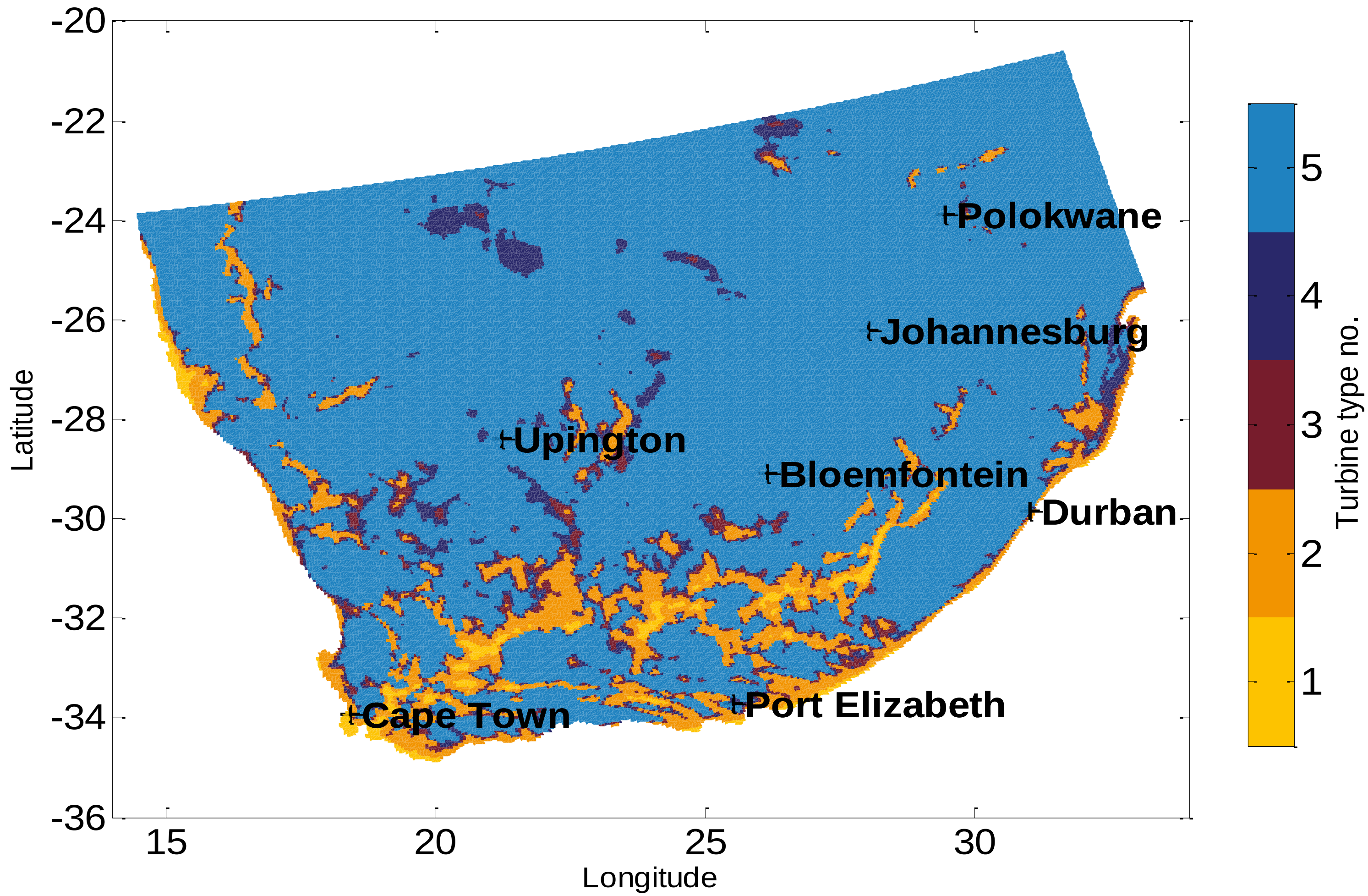
In each of the 50 000 pixels of 5x5 km size across the country, a wind farm placed consisting of turbines of type 1, 2, 3, 4 or 5



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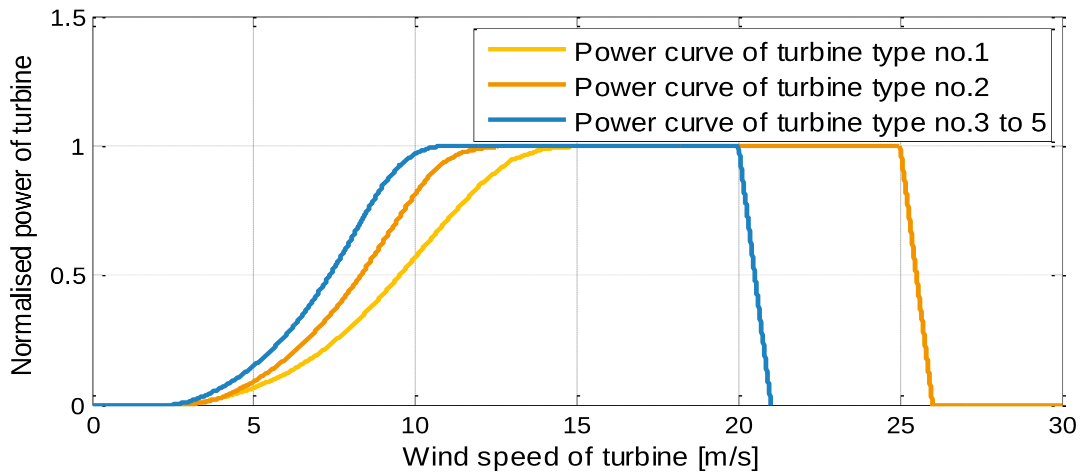
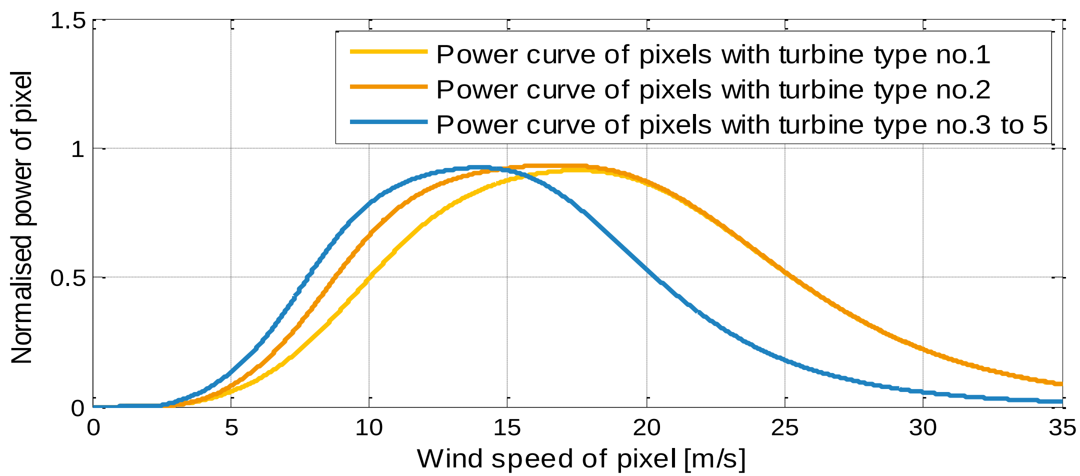
Power curves of single wind turbines (top) and for simulated wind farms on a 5km x 5km pixel (bottom) by turbine type



Wind turbine charateristic 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

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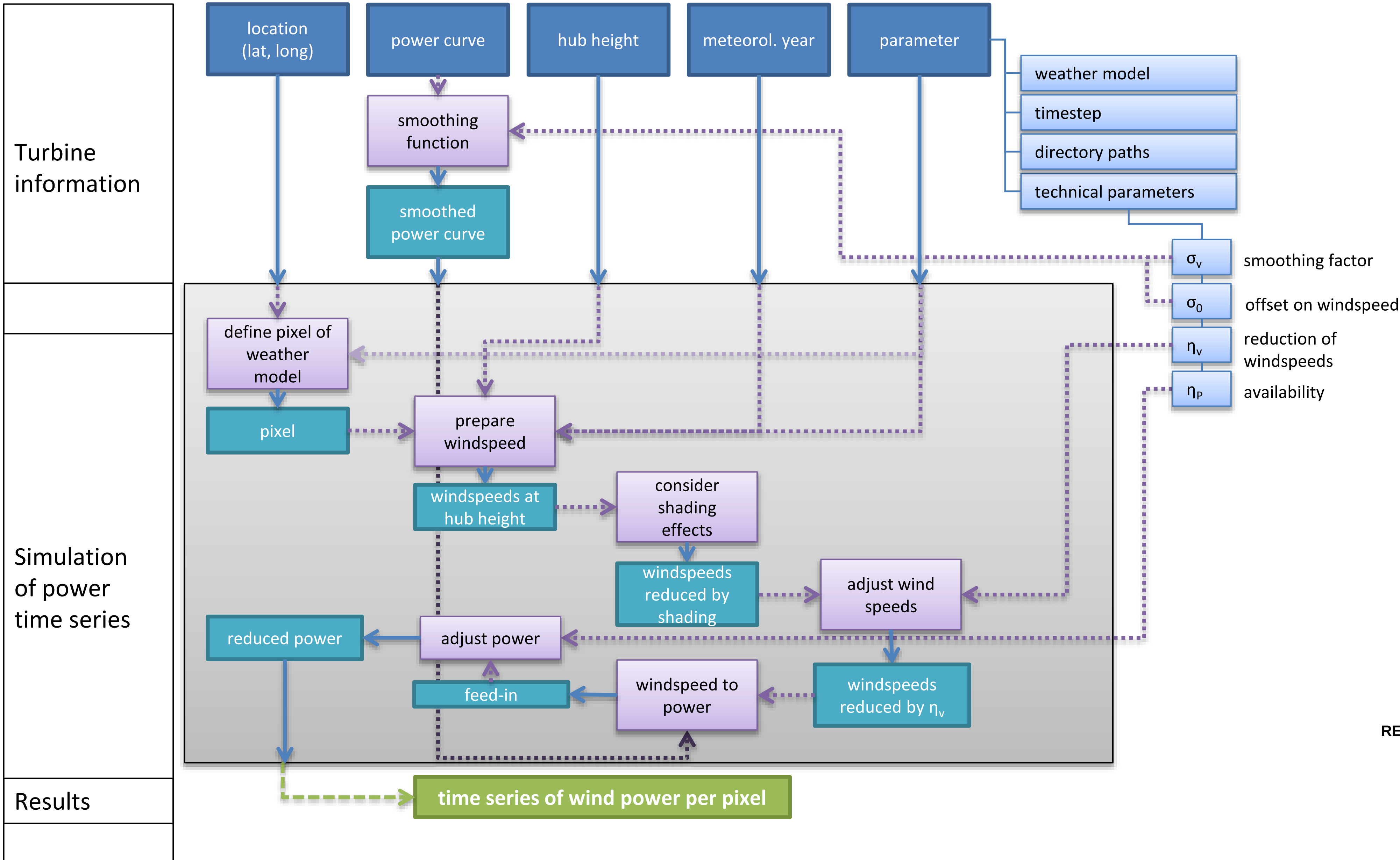
Generation of time series of wind feed-in



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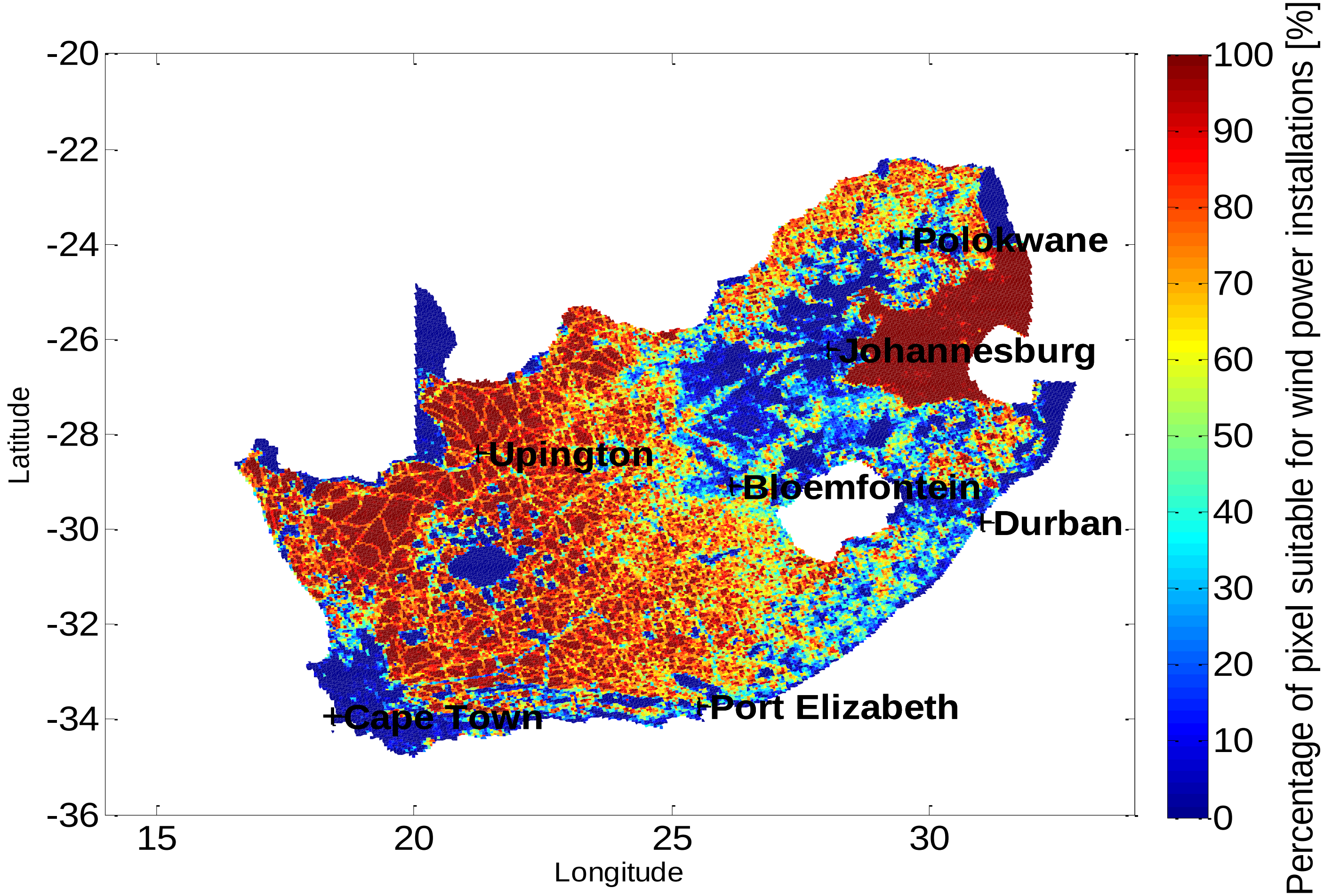
Share of each 5x5 km² pixel that is suitable for installation of wind farm after excluding areas reserved for other functions

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.

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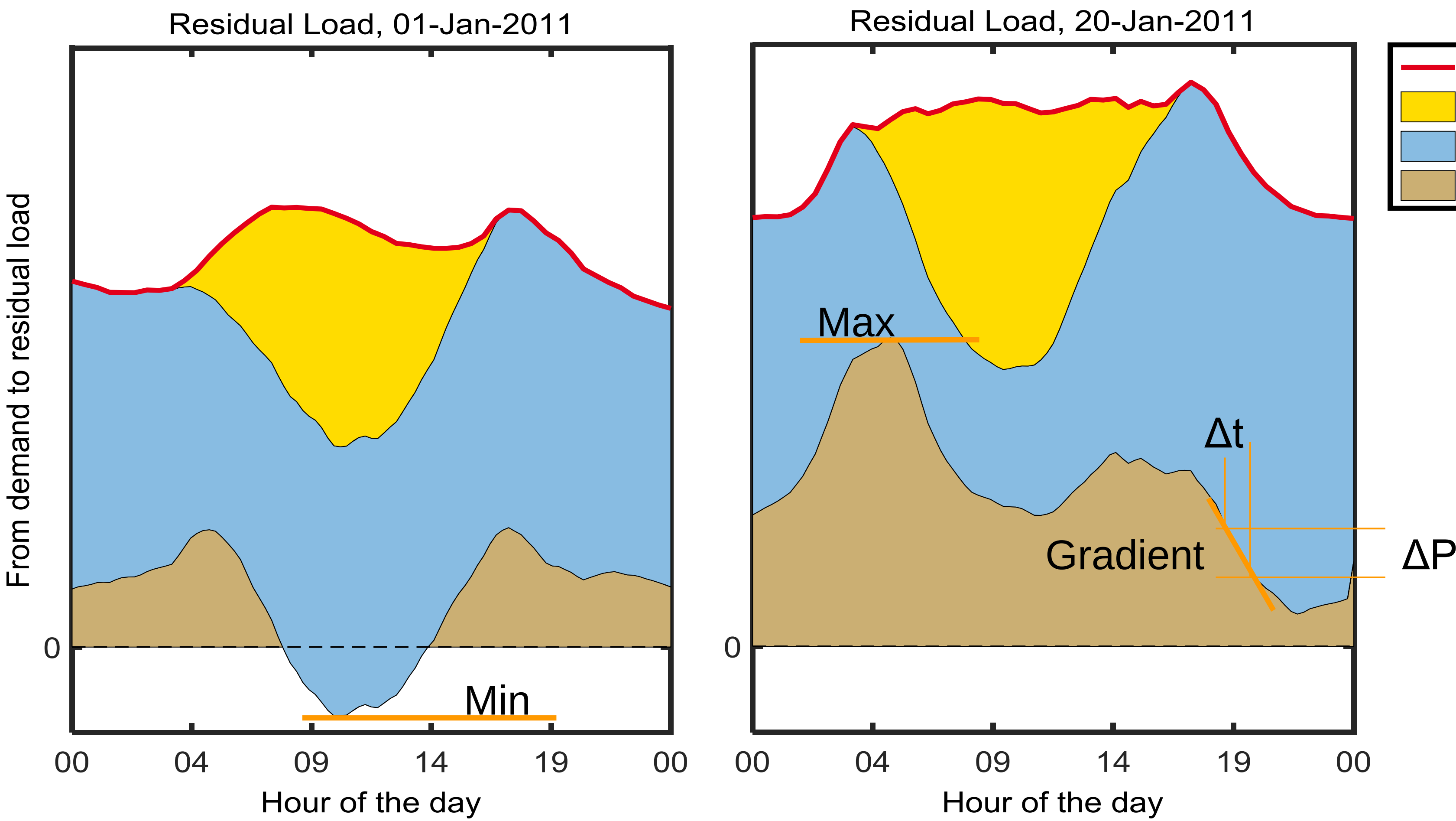
Definition:
"Residual load" needs to be supplied by dispatchable power

Residual load (*t*) = Load (*t*) – PV feed-in (*t*) – Wind feed-in (*t*)



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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

Load for all scenarios: 500 TWh/yr

Solar PV energy penetration (one fixed spatial distribution defined)	Wind energy penetration: **50 TWh/yr** *(~15 GW)*	**100 TWh/yr** *(~30 GW)*	**250 TWh/yr** *(~75 GW)*
40 TWh/yr *(~21 GWp)*	• VRE Share: 18% • 9 Wind distribution scenarios	• VRE Share: 28% • 9 Wind distribution scenarios	• VRE Share: 58% • 9 Wind distribution scenarios
80 TWh/yr *(~42 GWp)*	• VRE Share: 26% • 9 Wind distribution scenarios	• VRE Share: 36% • 9 Wind distribution scenarios	• VRE Share: 65% • 9 Wind distribution scenarios
200 TWh/yr *(~104 GWp)*	• VRE Share: 44% • 9 Wind distribution scenarios	• VRE Share: 52% • 9 Wind distribution scenarios	• VRE Share: 75% • 9 Wind distribution scenarios

Note: VRE = variable renewable energy, which is solar PV and wind (the <u>only two</u> variable power sources; dispatched by the weather and not be 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

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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

1. Enviromental Impact Assessment areas   2. Renewable Energy Development Zone

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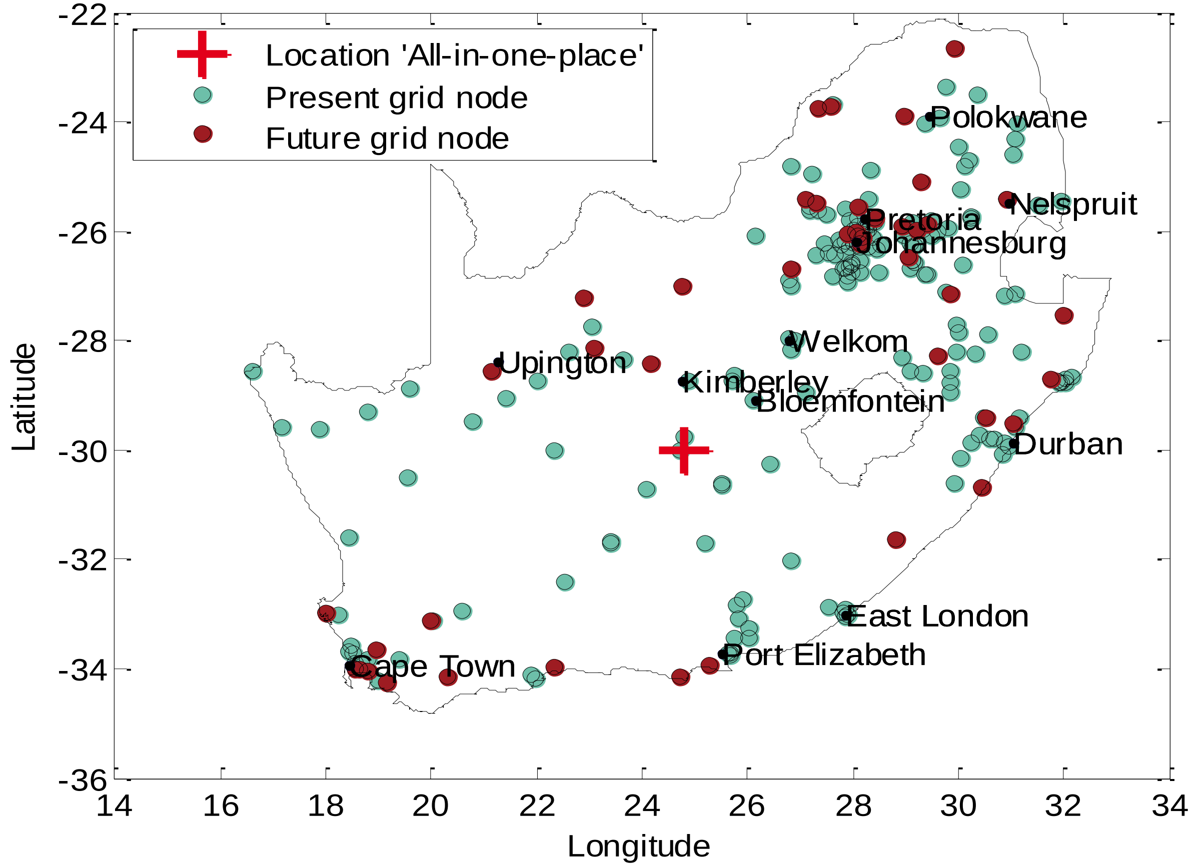
Present and future grid nodes for grid-oriented scenarios and the individual location selected for ‘All-in-one-place’ scenario

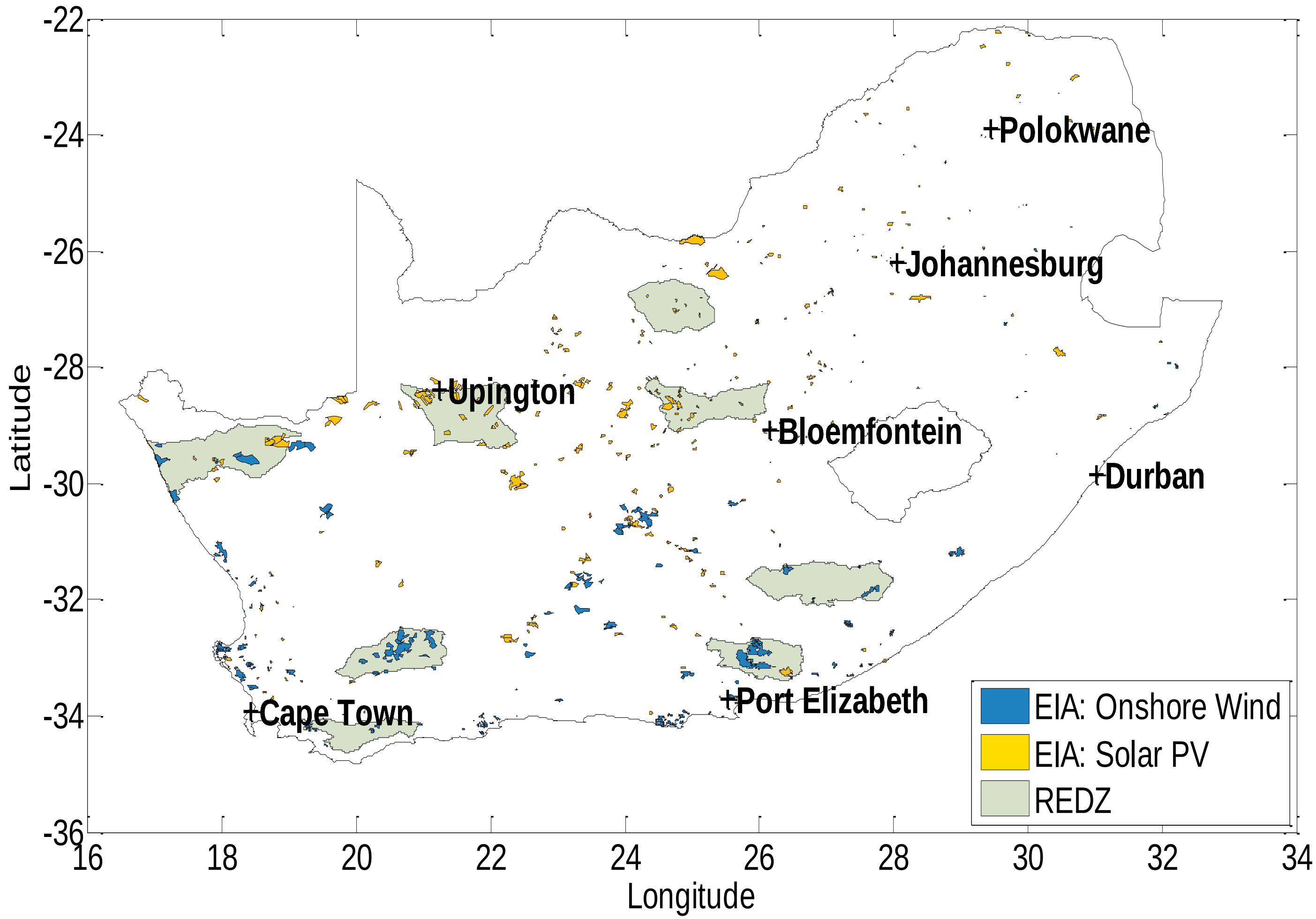
1b
3a
3b



REV 1

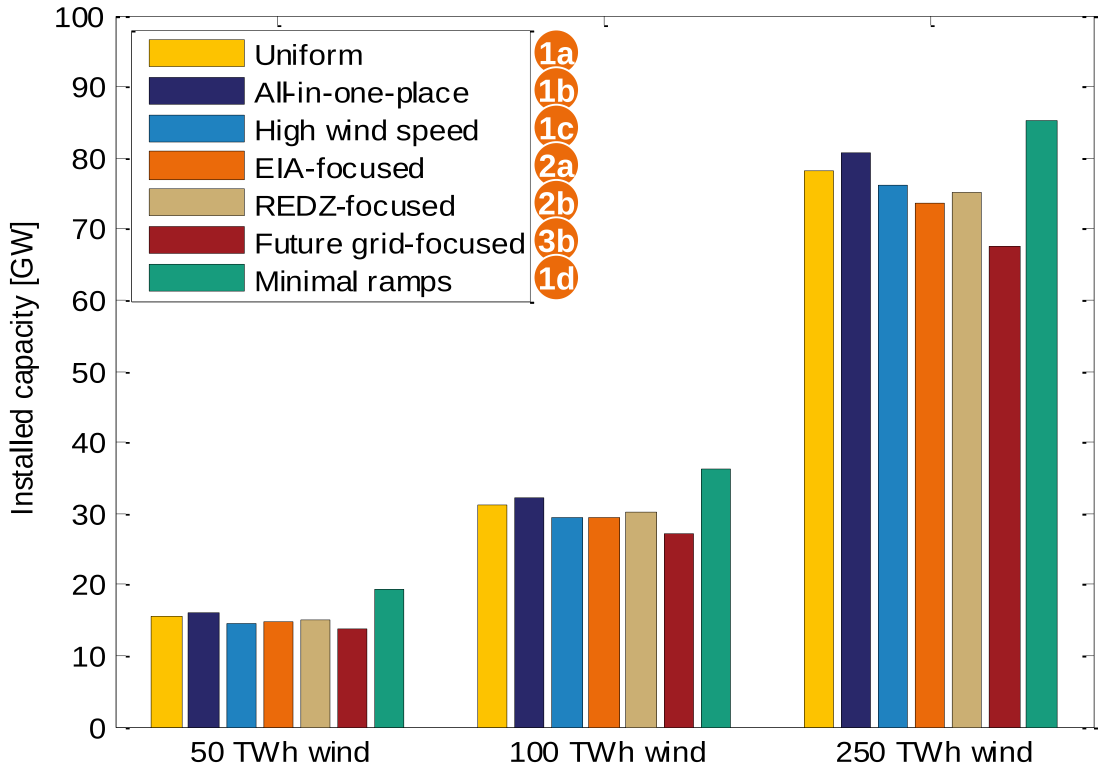
Areas used for the designated-areas scenarios

2a
2b
2c



REV 1

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



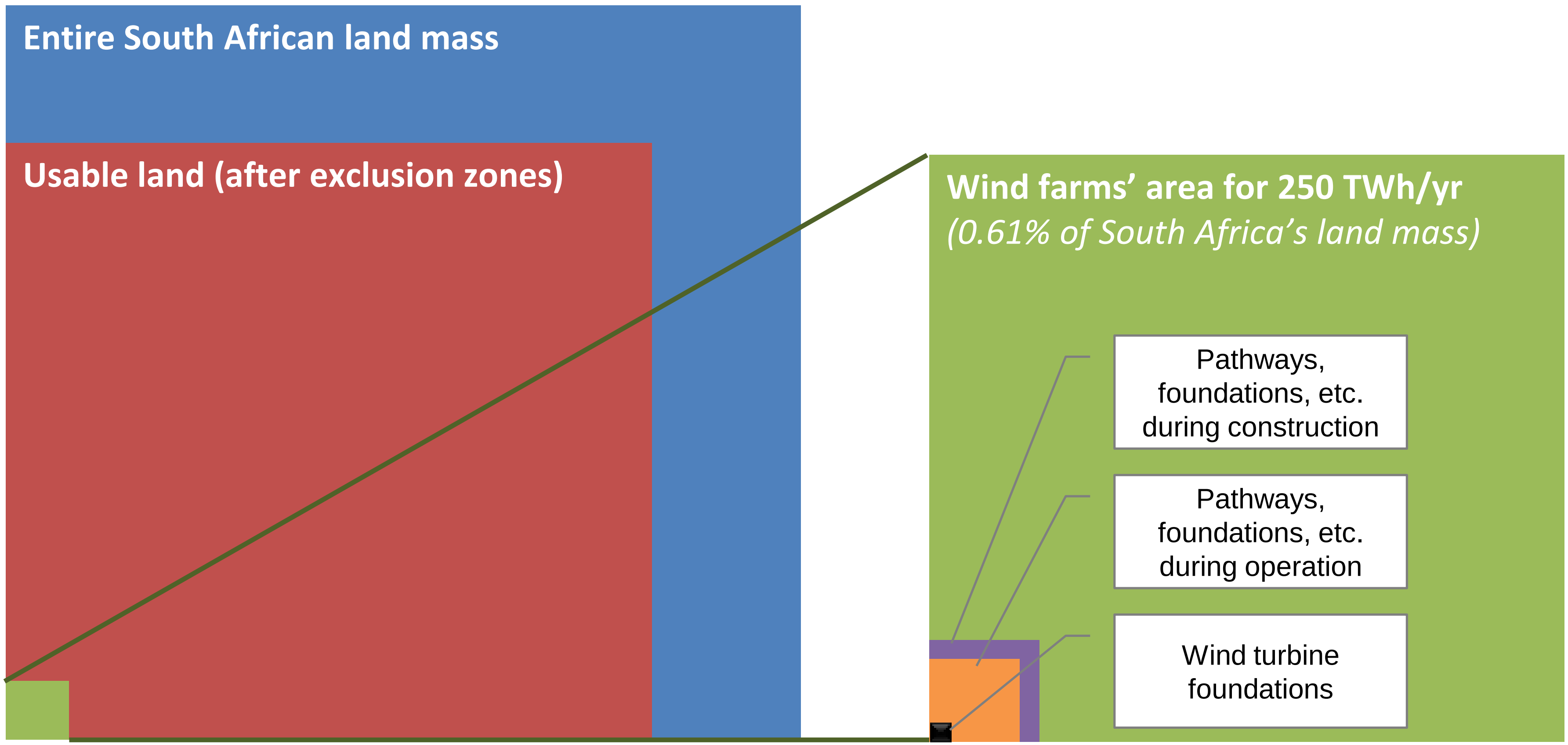
→ 50 TWh/yr of wind electricity requires 1 500 km² = 0.12% of South Africa's landmass

→ 250 TWh/yr of wind electricity requires 7 500 km² = 0.61% of RSA's landmass

REV 1

Only a small portion of wind farm area is actually utilised land

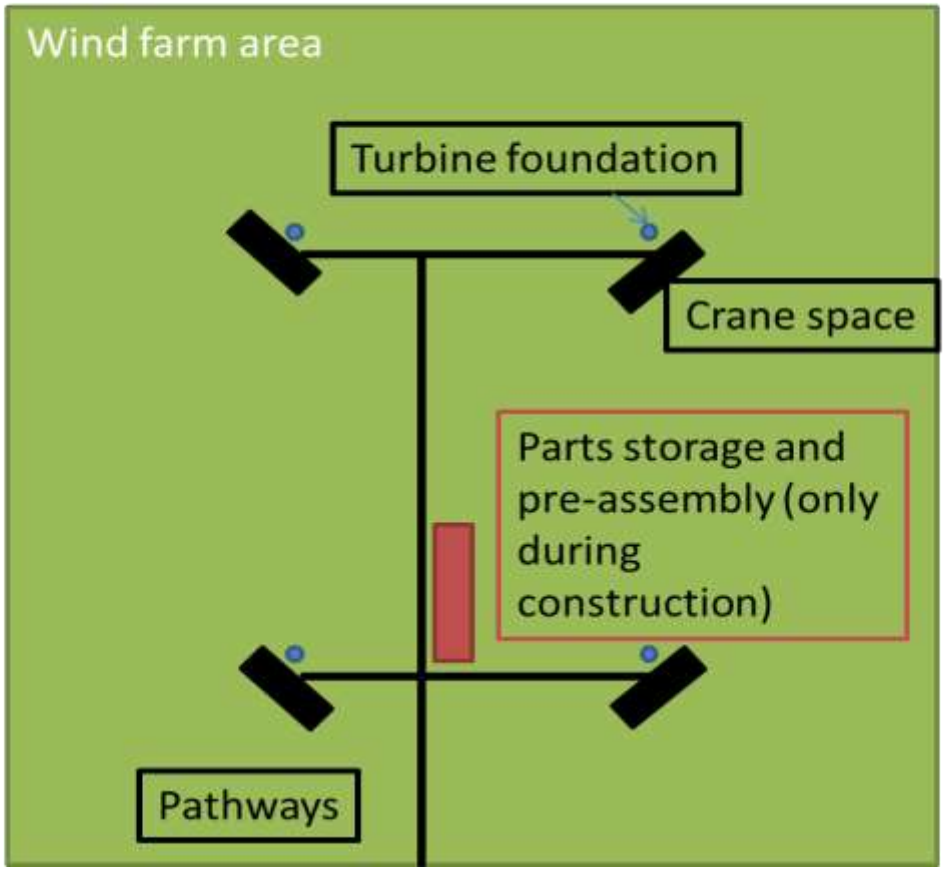
Illustration of space consumed by wind farms in a 250 TWh/yr wind energy scenario



REV 1

During construction, actual land used is already low

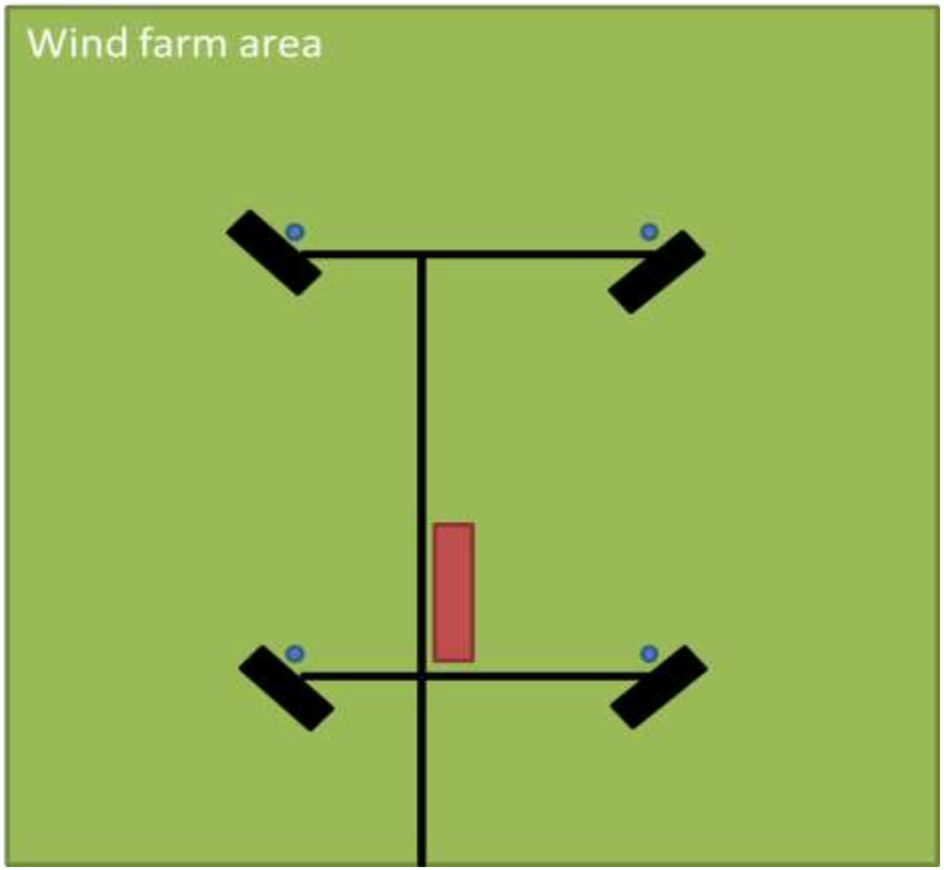
Illustration of land required during construction of a wind farm



REV 1

During wind farm operation, the land actually used is very low

Illustration of land required during operation of a wind farm



	% of the wind farm area	% of South African land mass *(for a 75 GW wind fleet that yields 250 TWh/yr)*
Wind farm area	100%	0.61% *(7 500 km²)*
Ways, foundation during construction	3%	0.018% *(225 km²)*
Permanently used	2%	0.012% *(150 km²)*
Wind turbine foundations	0.1%	0.0008% *(10 km²)*

REV 1

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)

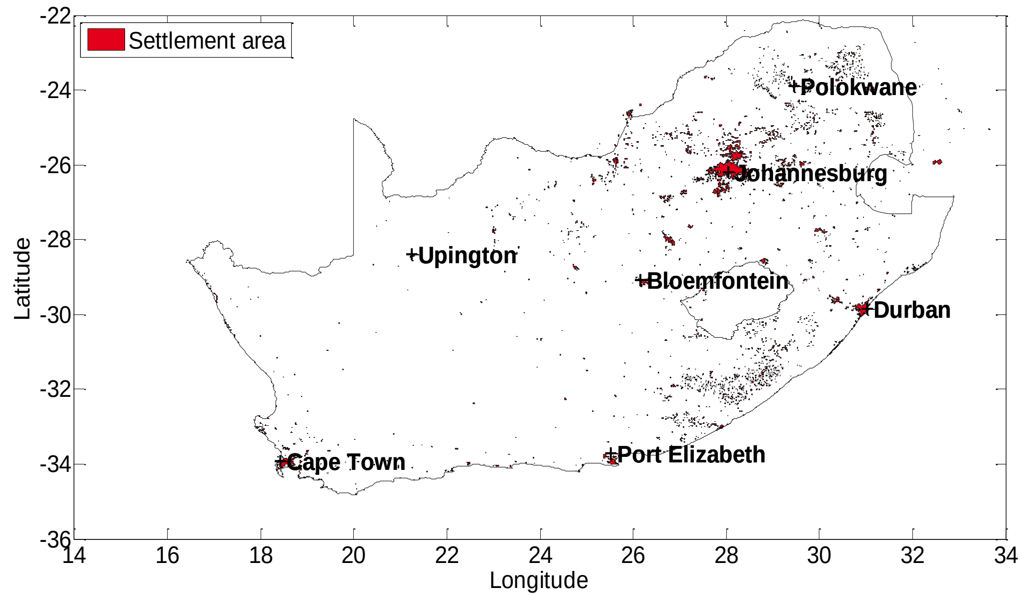
- 73 GW installed capacity
- 136 TWh/yr electricity generation

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.

REV 1

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

	Penetration level 1	Penetration level 2	Penetration level 3
	40 TWh/yr	80 TWh/yr	200 TWh/yr
Distributed (70%)	15 GW	29 GW	73 GW
Utility scale (30%)	6 GW	13 GW	31 GW
Total	**21 GW**	**42 GW**	**104 GW**

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.

REV 1

Agenda

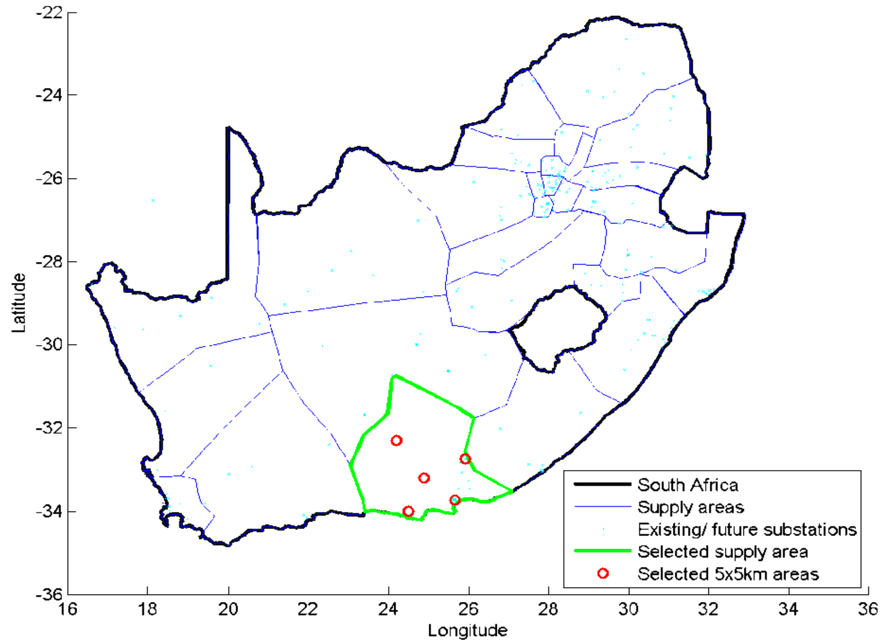
1. Introduction
2. Data
3. Methodology
4. Scenarios
5. **Results**
   I. Case Study Supply Area Port Elizabeth
   II. Aggregation Study
   III. Case Study Curtailment
6. Conclusions and Outlook

Case study:
Supply areas of South Africa

The South African transmission grid is divided into 27 supply areas

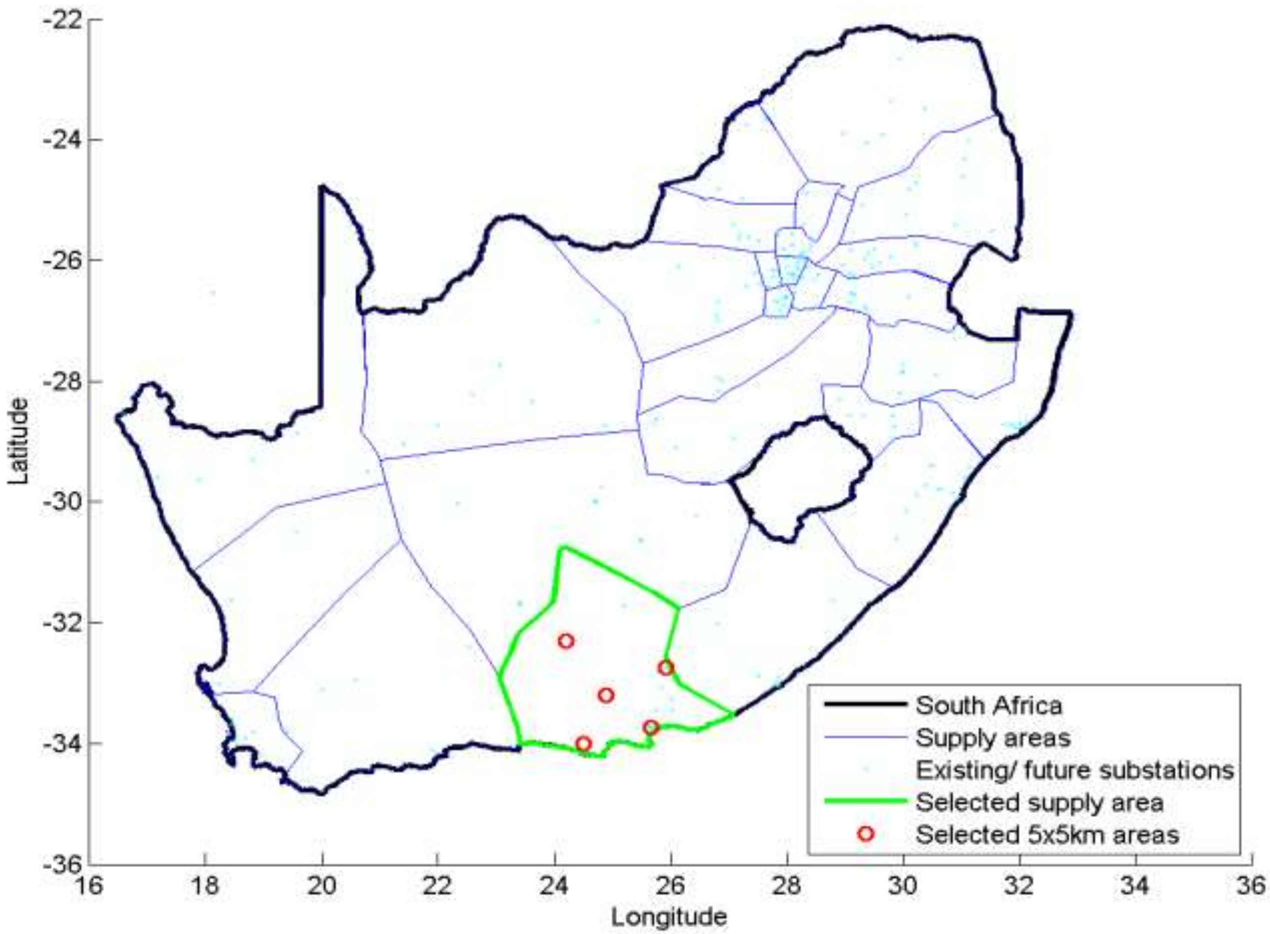
Each supply area comprises several grid nodes

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**

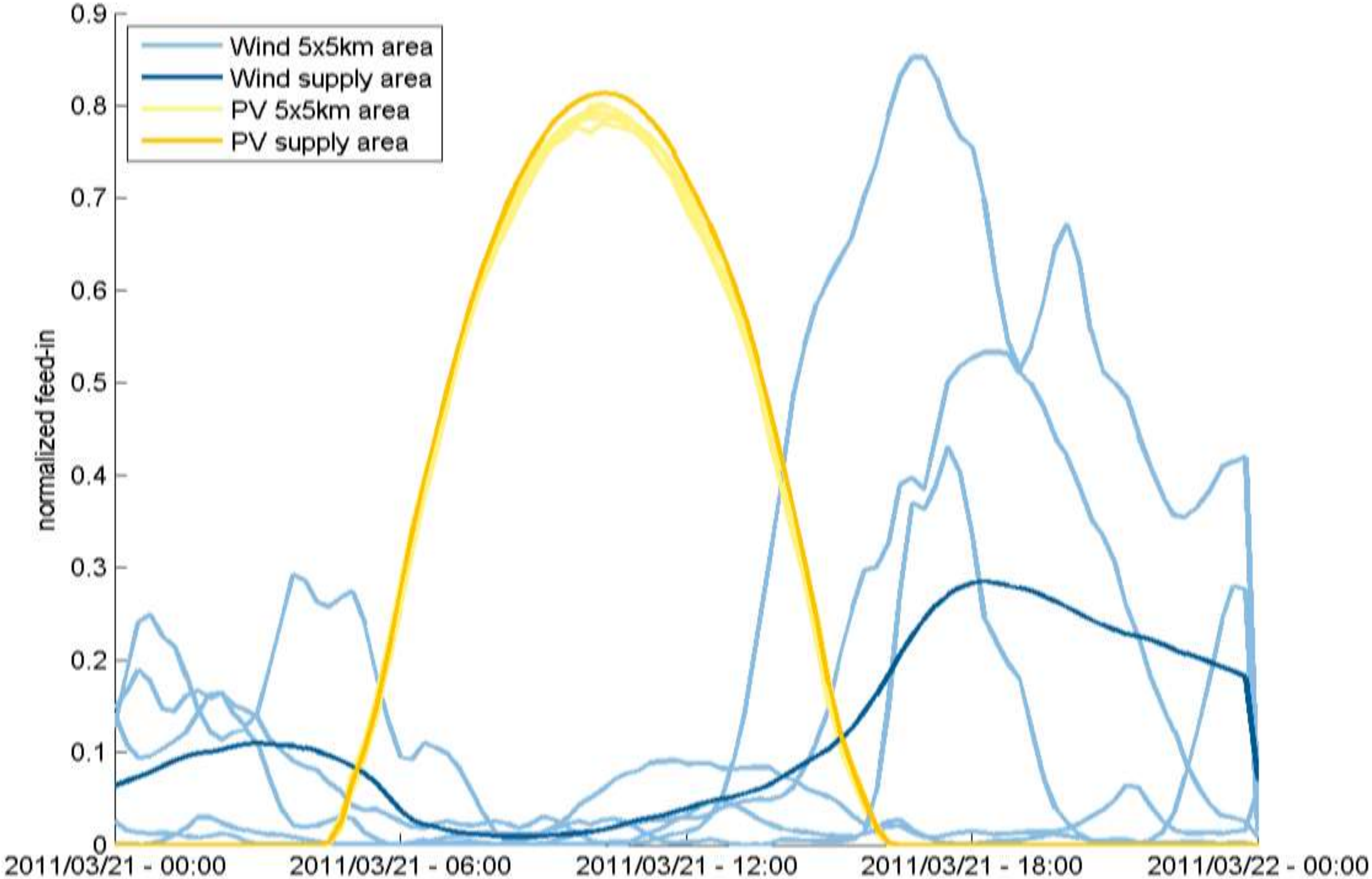
Case study:
Aggregation effects within the supply area of Port Elizabeth



REV 1

Case study: Spatial aggregation smoothens volatility

Simulated supply of 5 solar, 5 wind farms & of the entire Port Elizabeth area on 21 March 2011



REV 1

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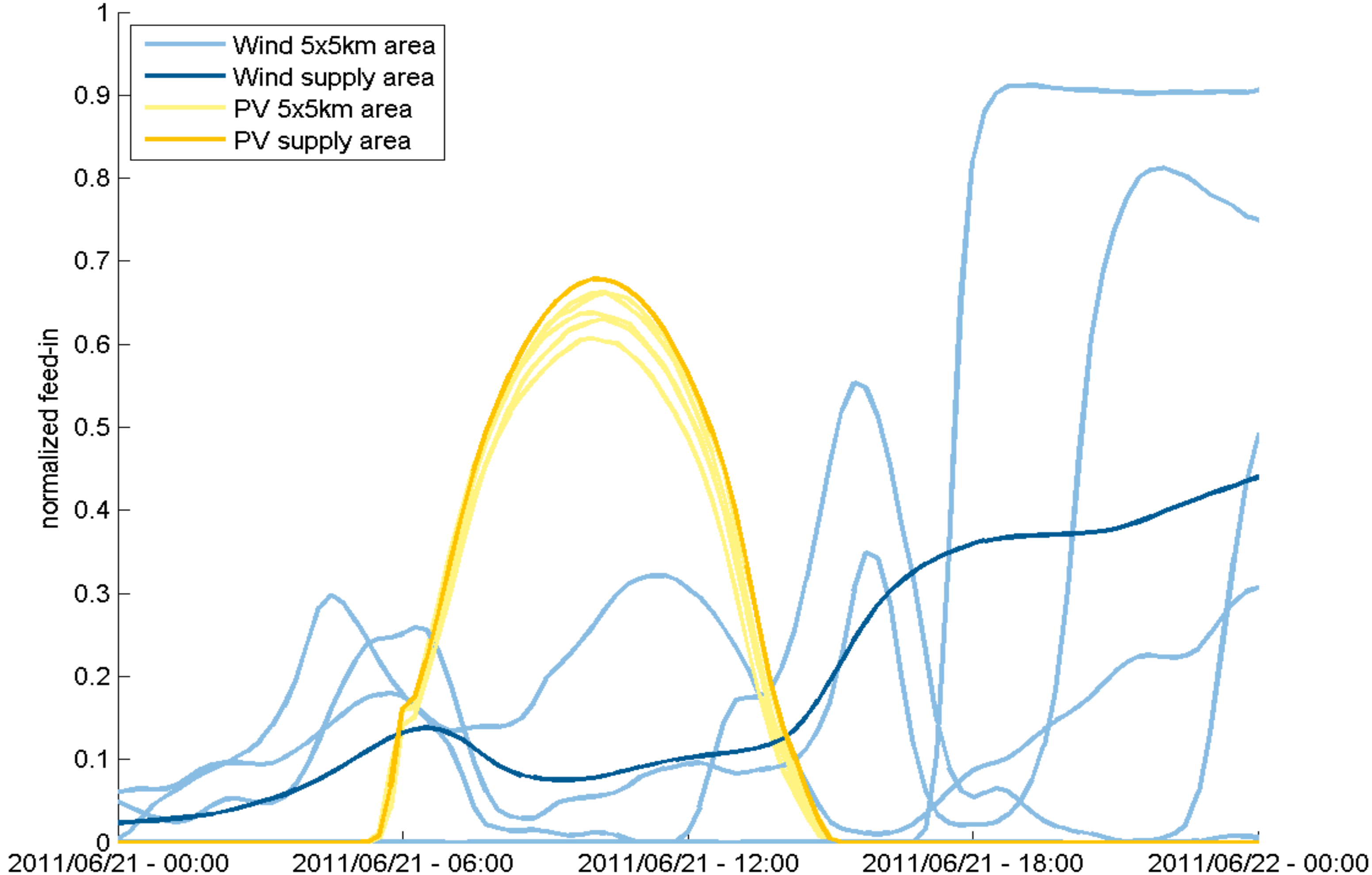
Case study: Spatial aggregation smoothens volatility

Simulated supply of 5 solar, 5 wind farms & of the entire Port Elizabeth area on 21 June 2011



REV 1

Case study: Spatial aggregation smoothens volatility

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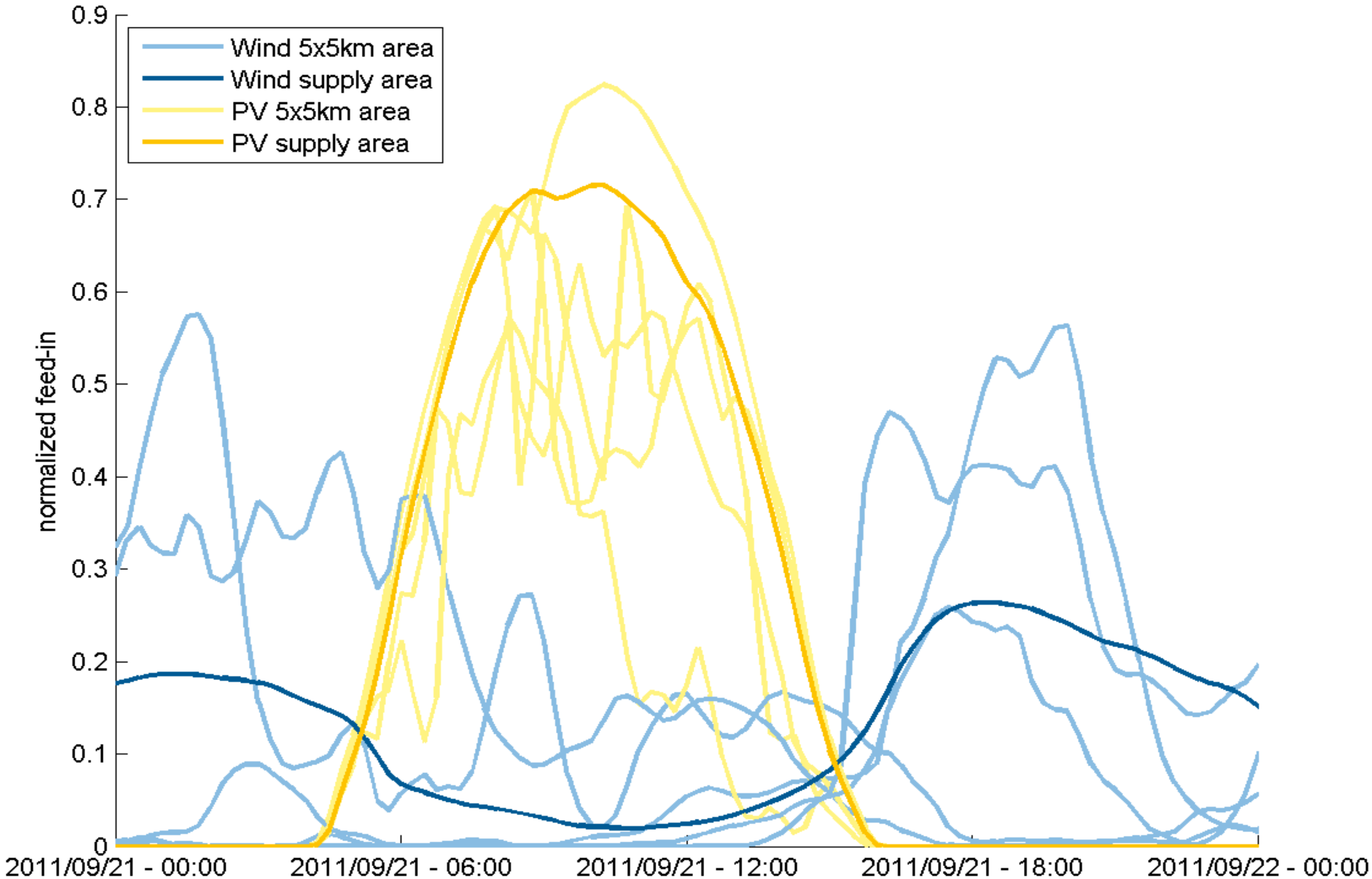
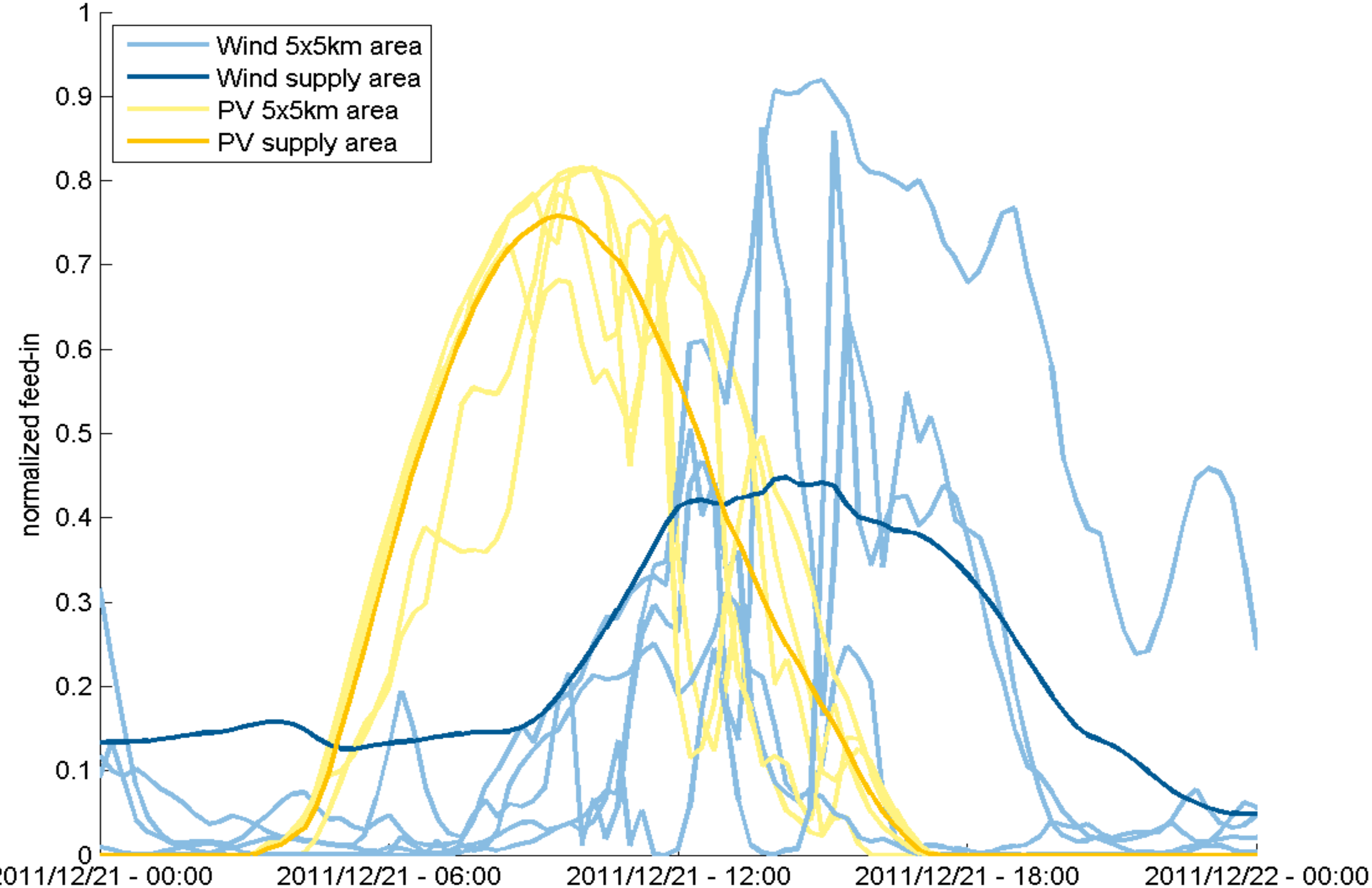


REV 1

Case study: Spatial aggregation smoothens volatility

Simulated supply of 5 solar, 5 wind farms & of the entire Port Elizabeth area on 21 December 2011



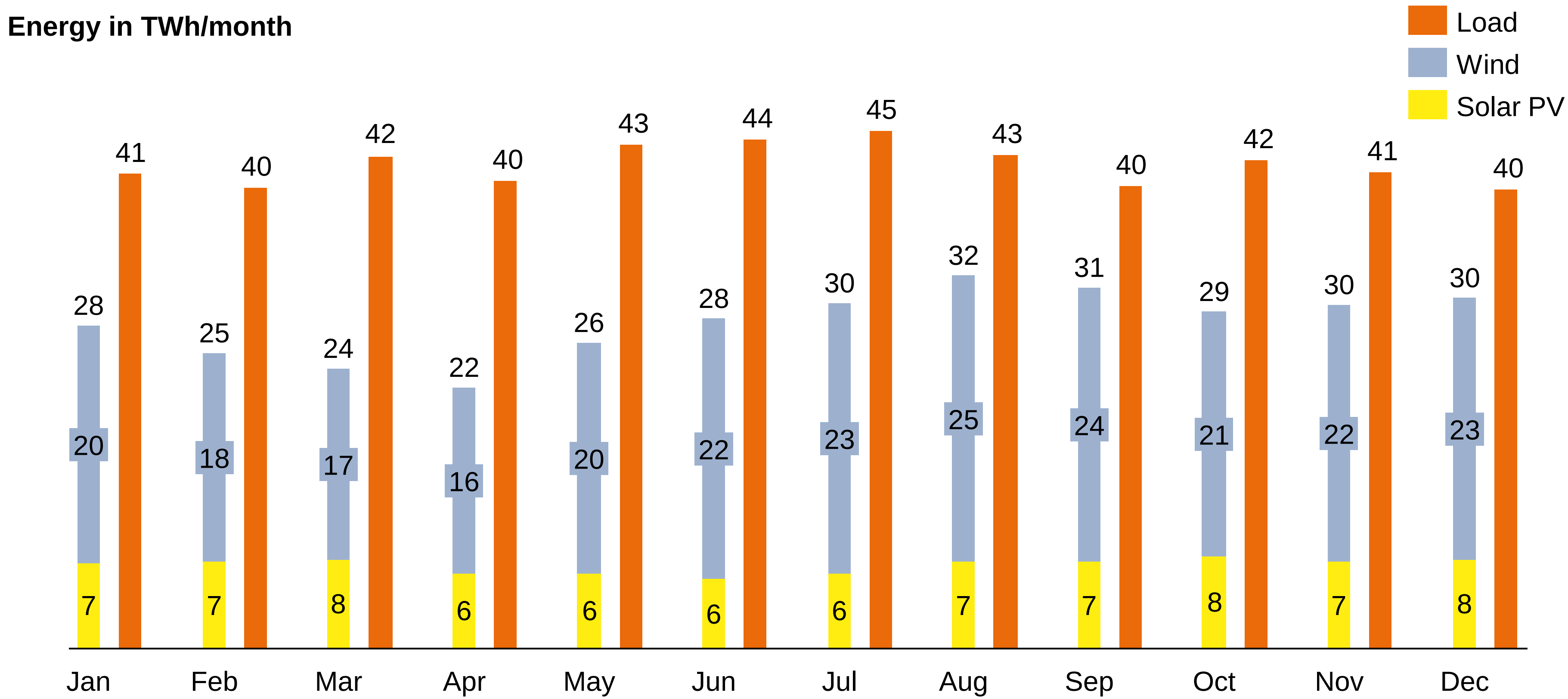
REV 1

Contents

REV 1

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



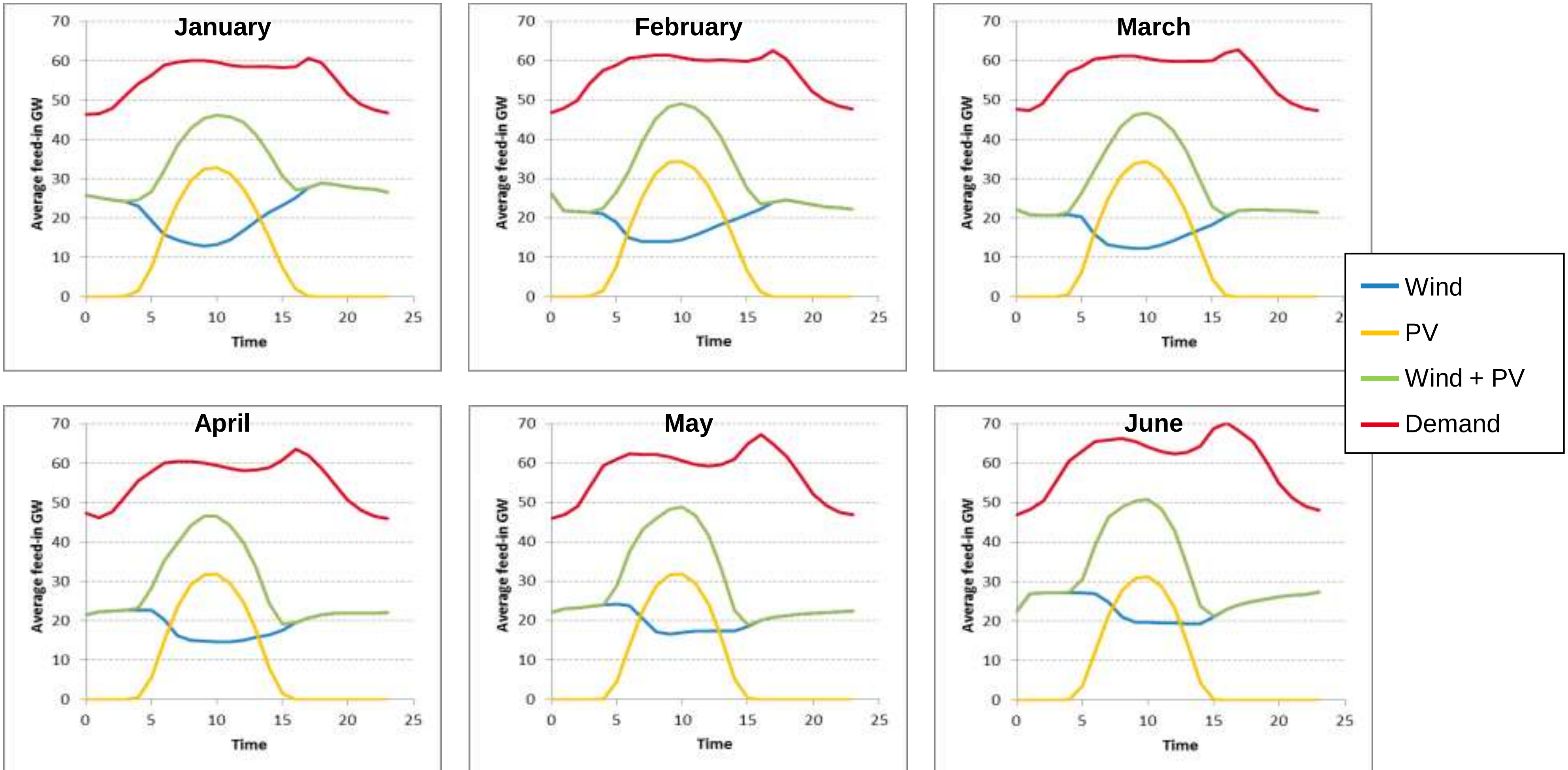
→ PV: nearly no seasonality

→ Monthly wind supply is correlated with the monthly fluctuations in demand

REV 1

Average wind profile generally with less output during the day and more during evening/night – complements well load & PV

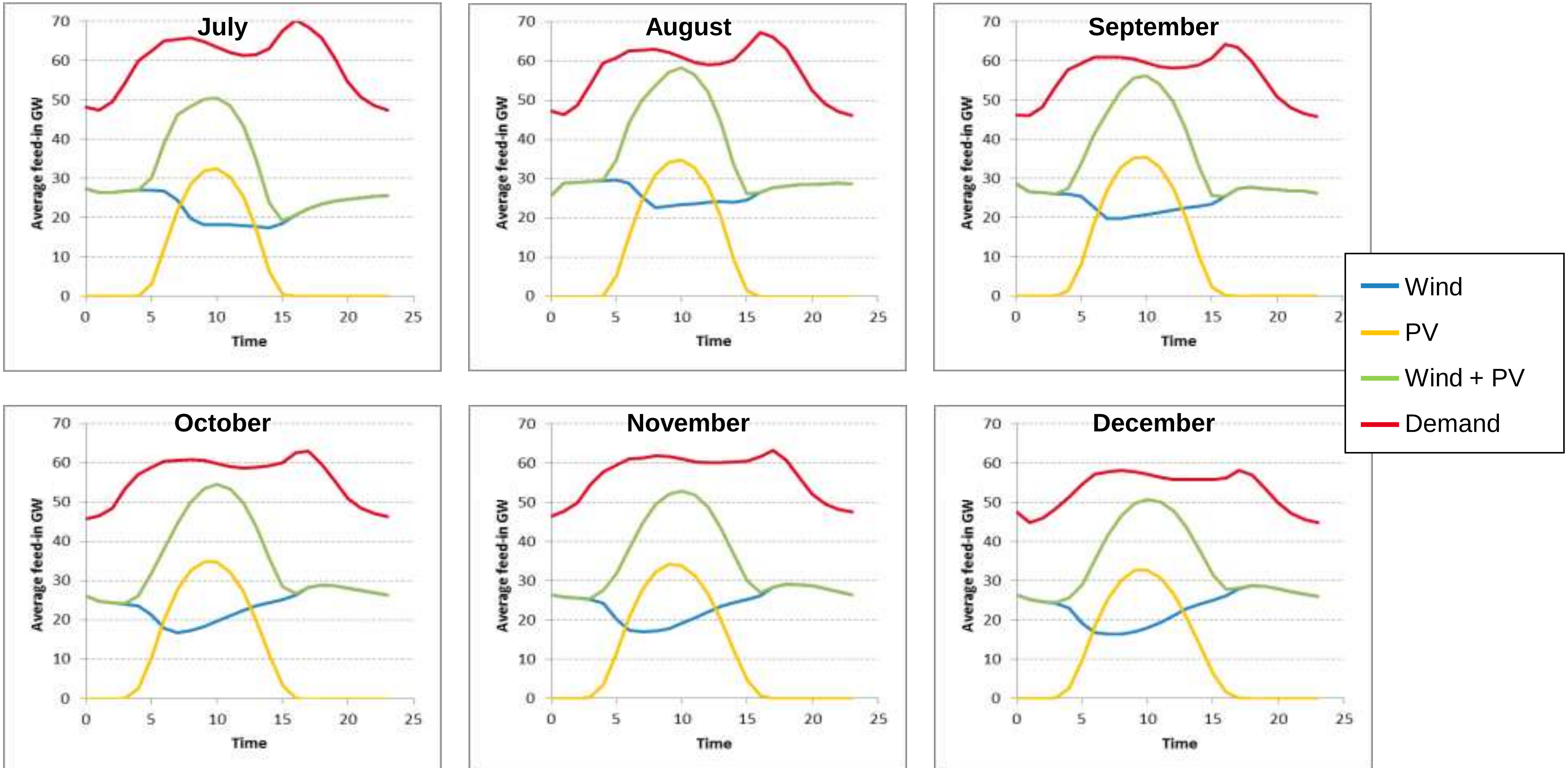
Simulated solar PV, wind, scaled load – grid-focused wind distribution: 250 TWh/yr, PV: 80 TWh/yr



REV 1

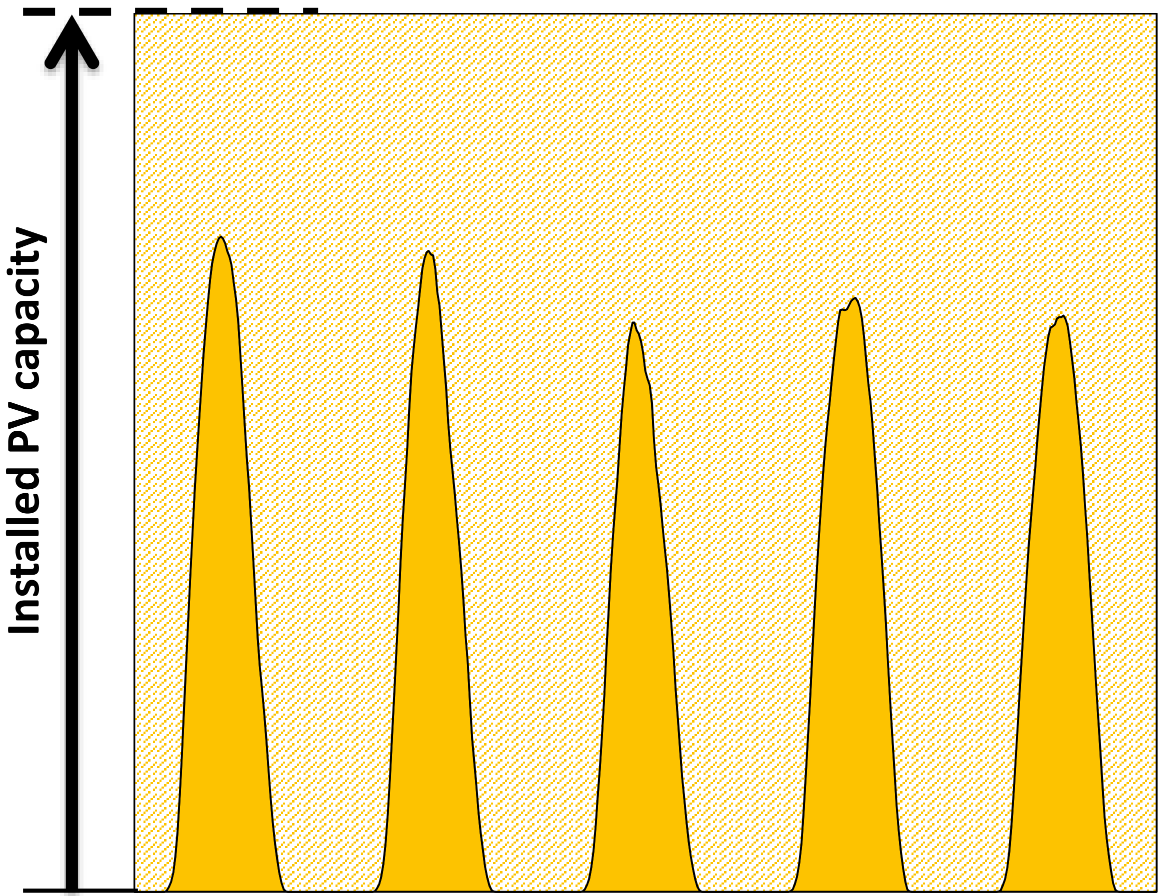
Average wind profile generally with less output during the day and more during evening/night – complements well load & PV

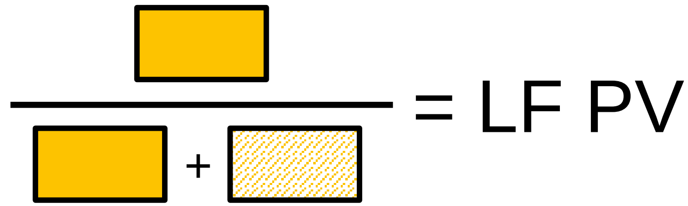
Simulated solar PV, wind, scaled load – grid-focused wind distribution: 250 TWh/yr, PV: 80 TWh/yr



REV 1

Definition of load factor: Total energy produced during a time period divided by (nominal power multiplied by time period)





REV 1

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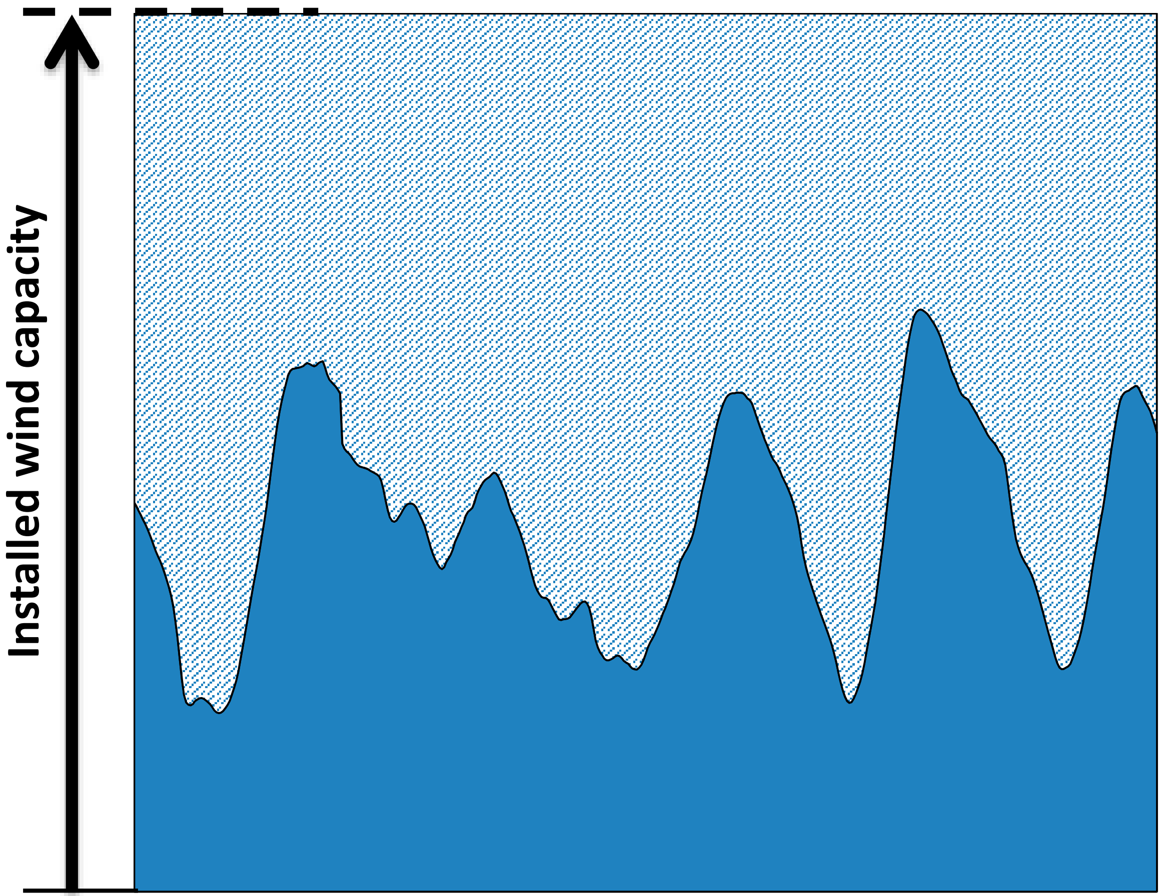
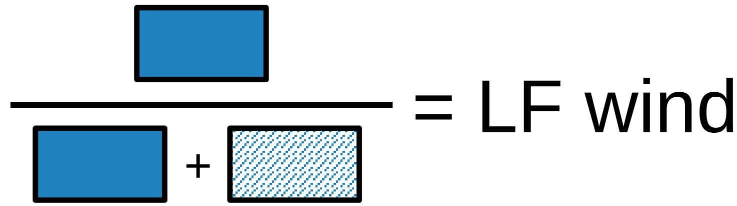
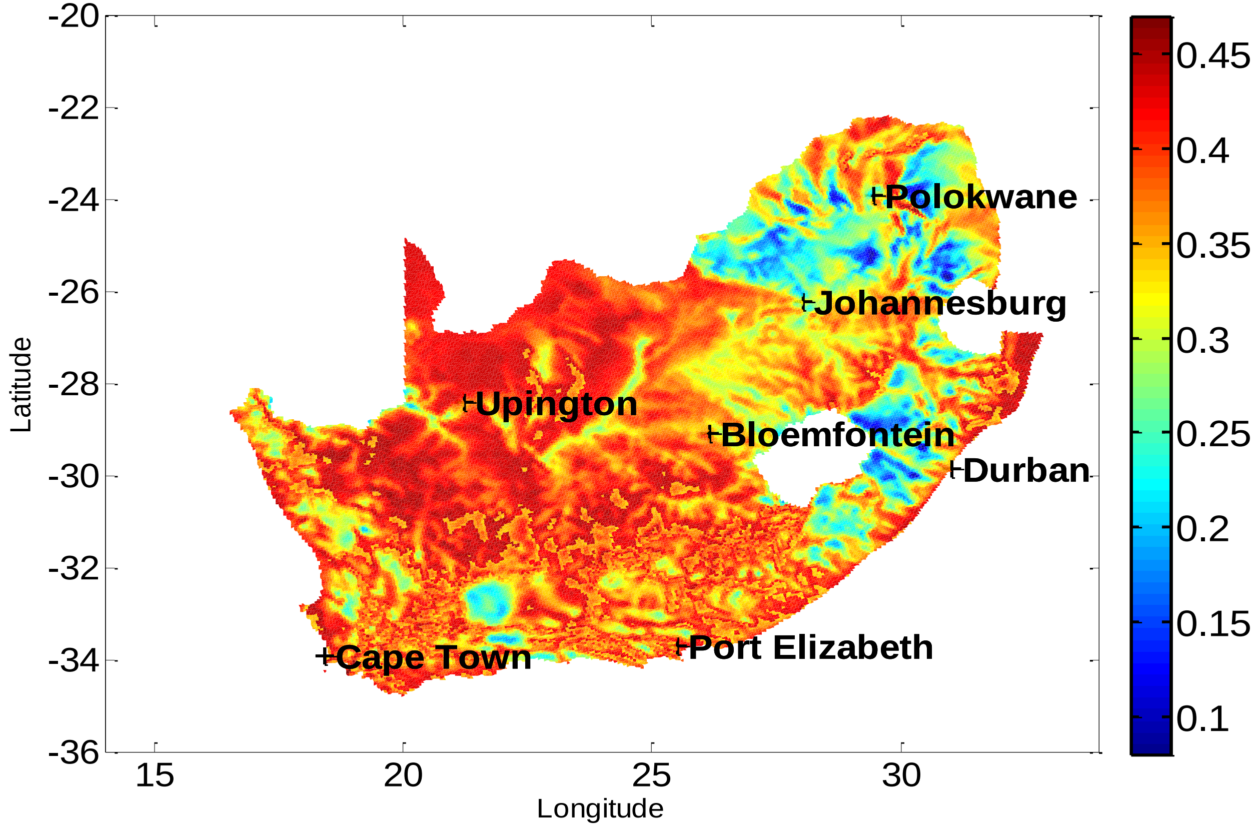




Placing a wind farm of best suited turbine type (1, 2, 3, 4 or 5) in each pixel: more than 30% load factor almost everywhere

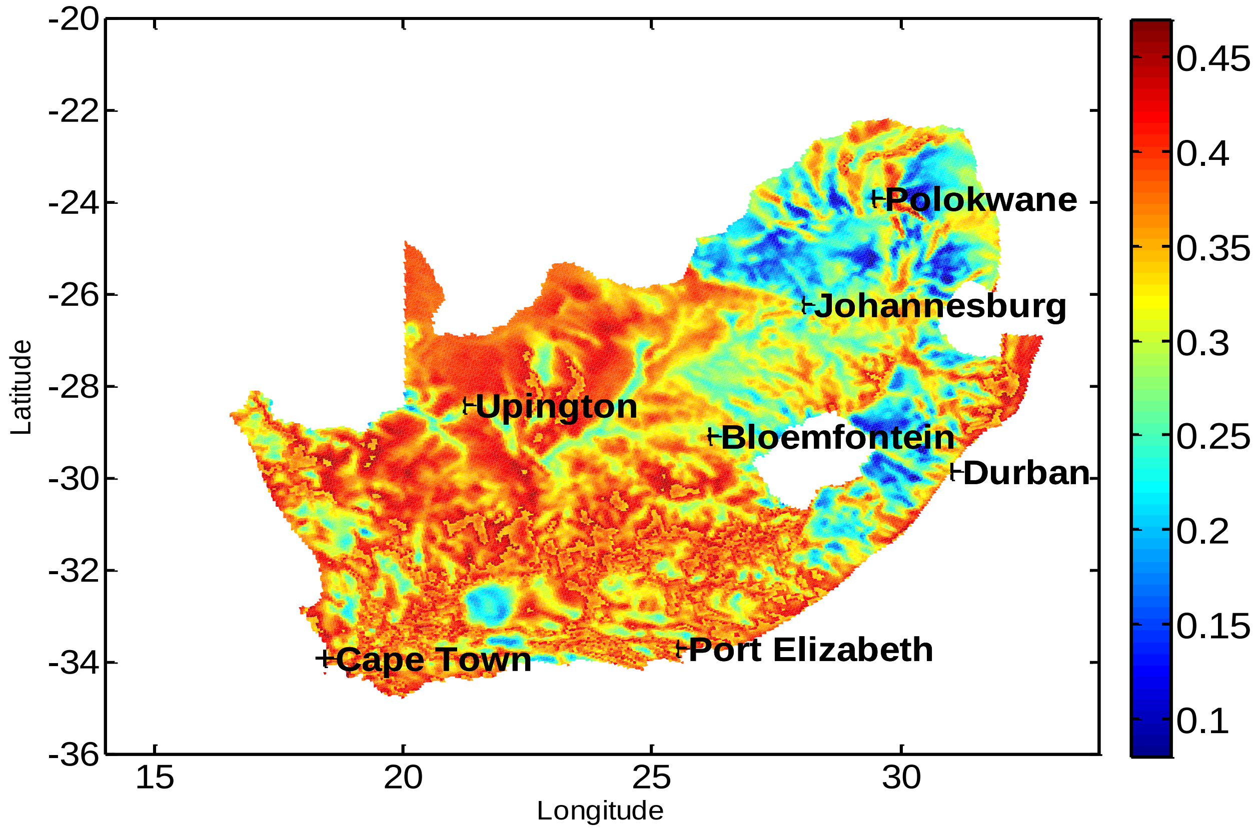


Average load factor from 2009-2013

→ Very high load factors of >30% nearly all over the country!

REV 1

Even when placing only high-wind-speed turbine types (1, 2, 3) in each pixel: more than 30% load factor in very wide areas



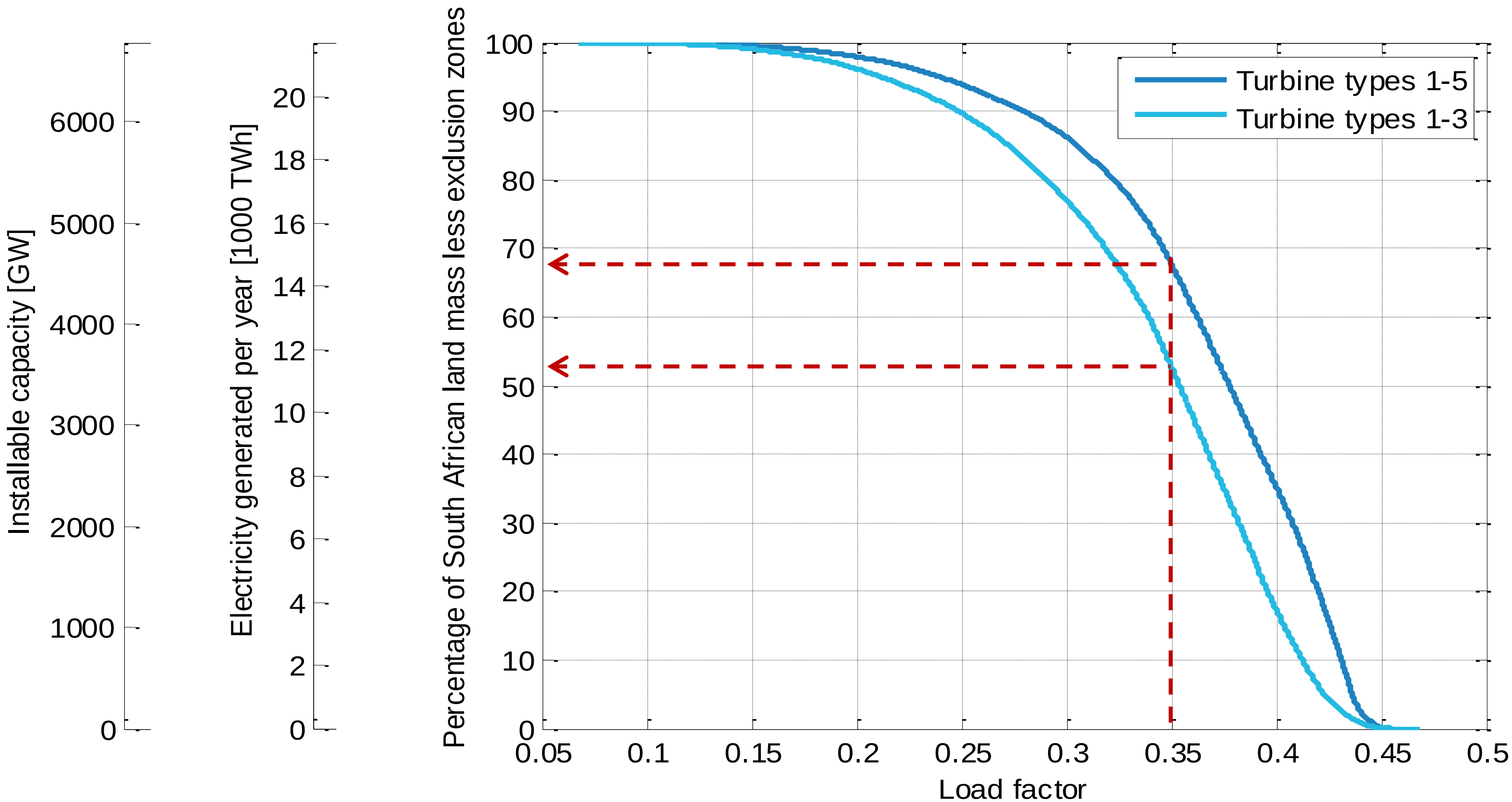
Average load factor from 2009-2013

→ Very high load factors of >30% nearly all over the country even for turbines types 1-3

REV 1

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



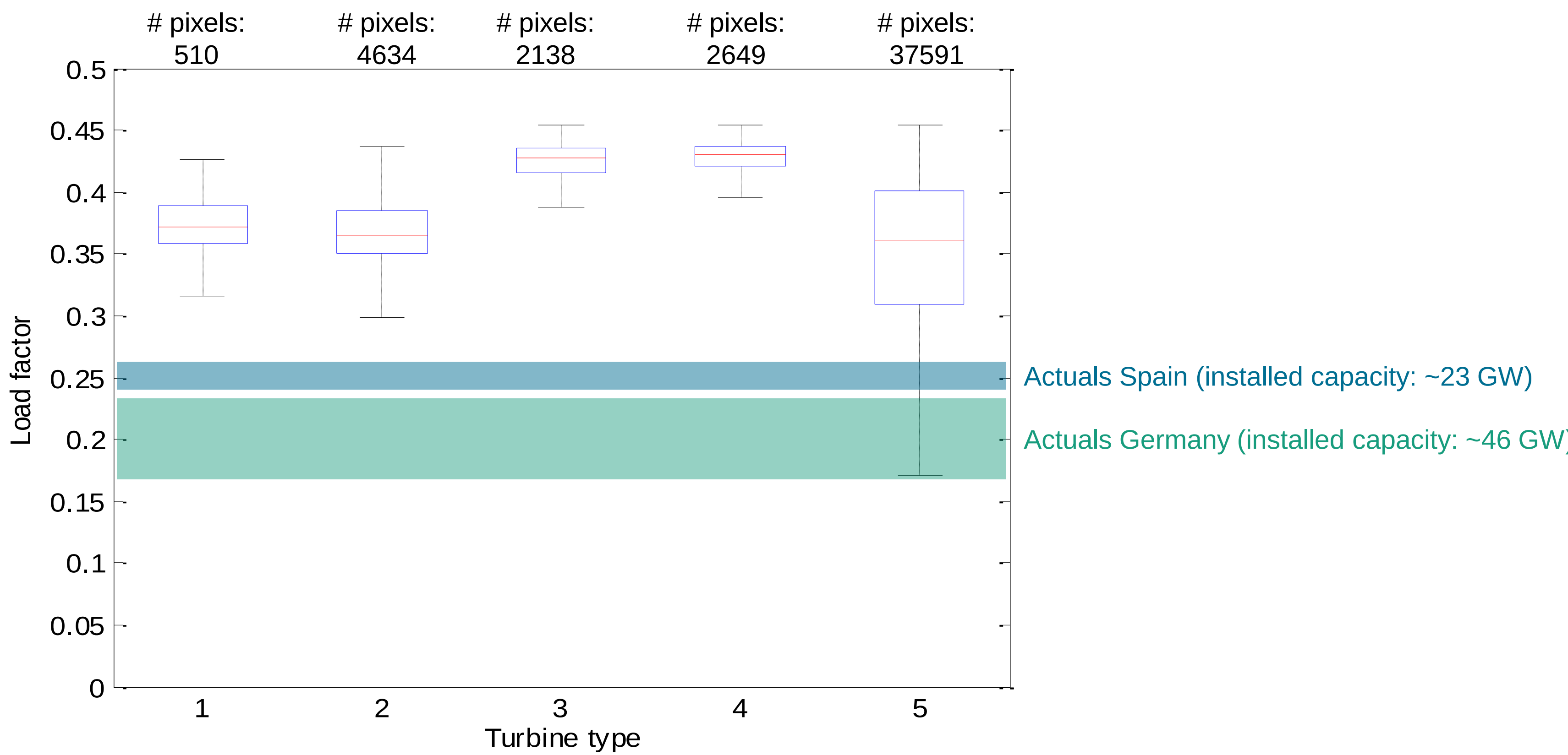
→ Installing turbine type 4 and 5 will cause higher costs but also increase load factors and electricity yield whilst consuming the same area

REV 1

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

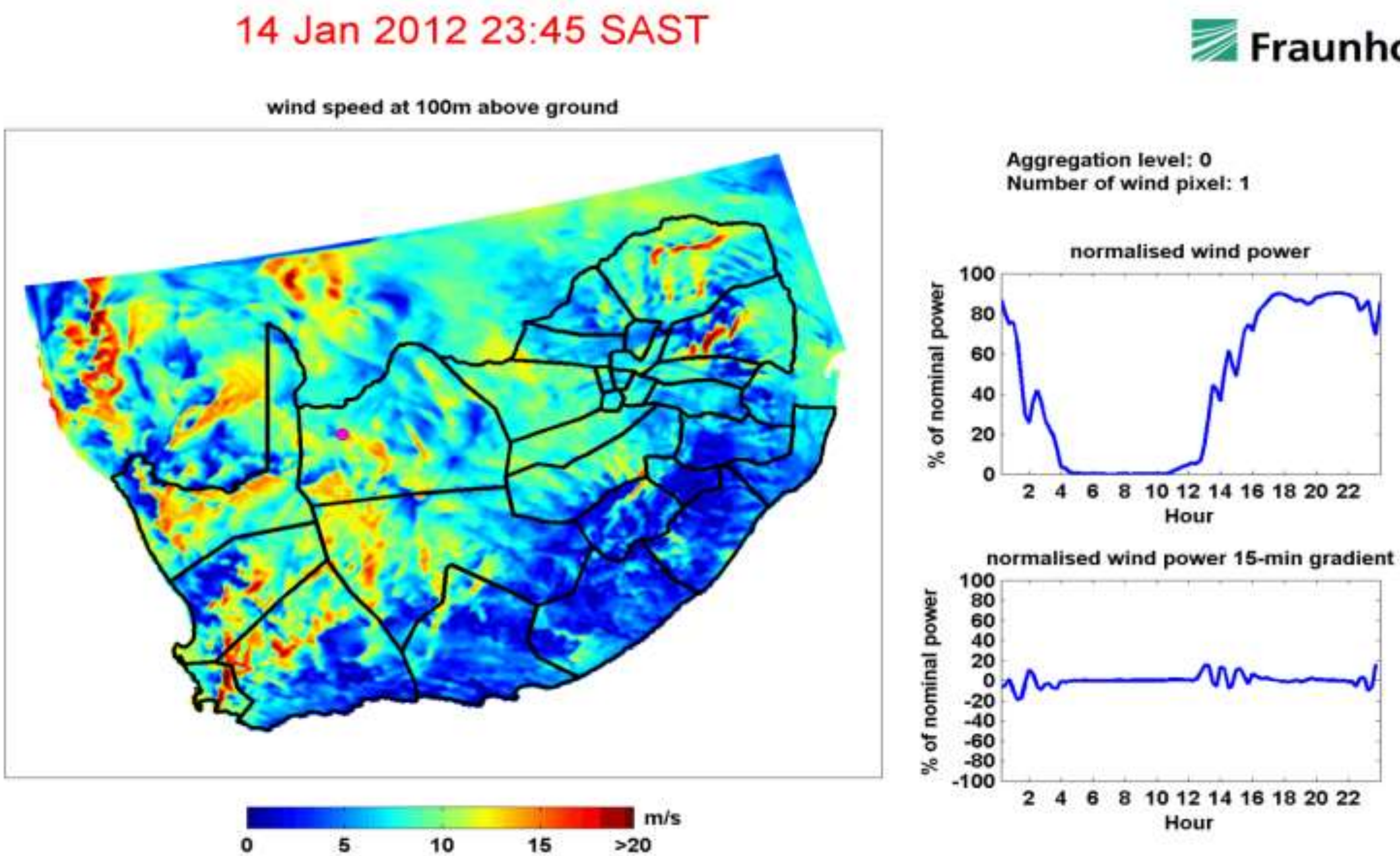
- Years: 2009-2013



REV 1

A single wind farm changes its power output quickly

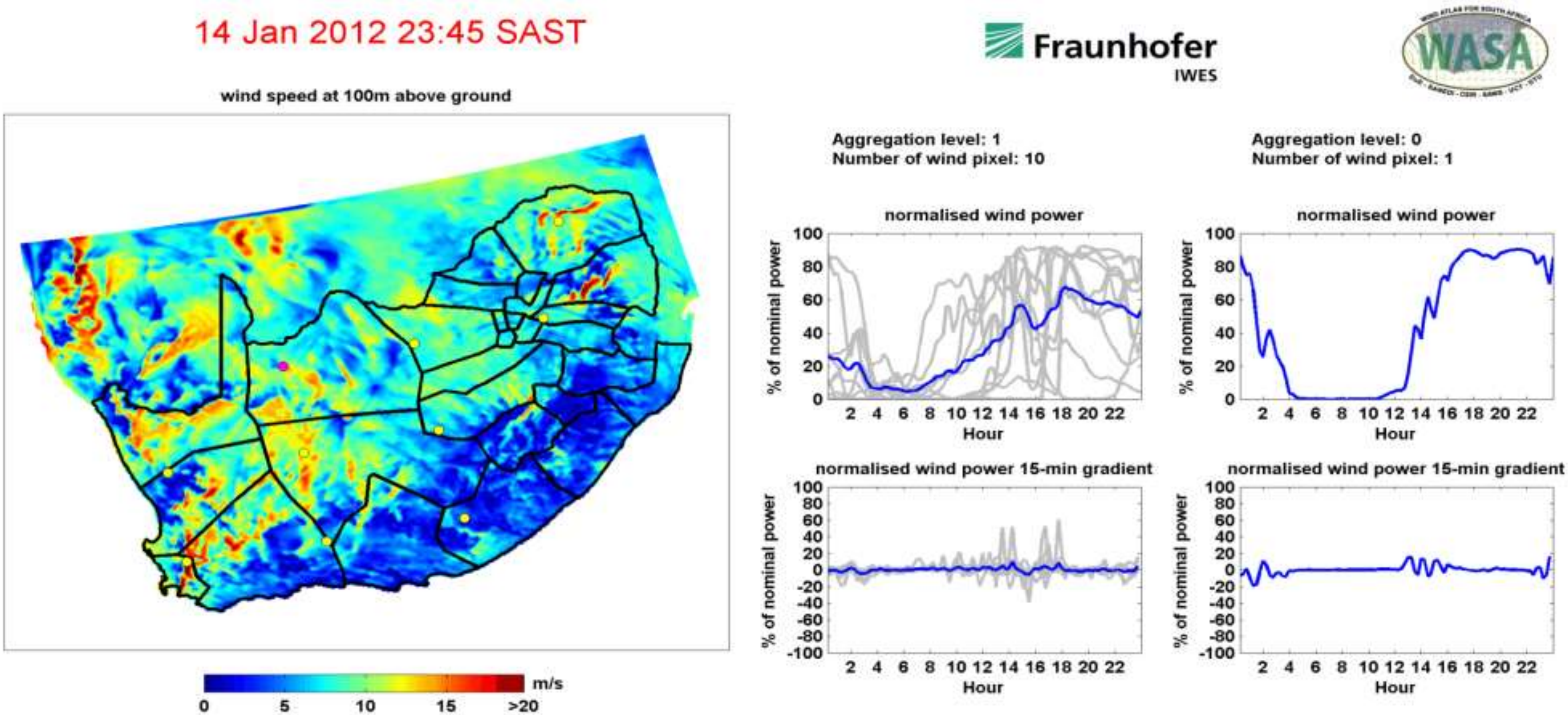
Simulated wind-speed profile and wind power output for 14 January 2012



REV 1

Aggregating just 10 wind farms' output already reduces short-term fluctuations

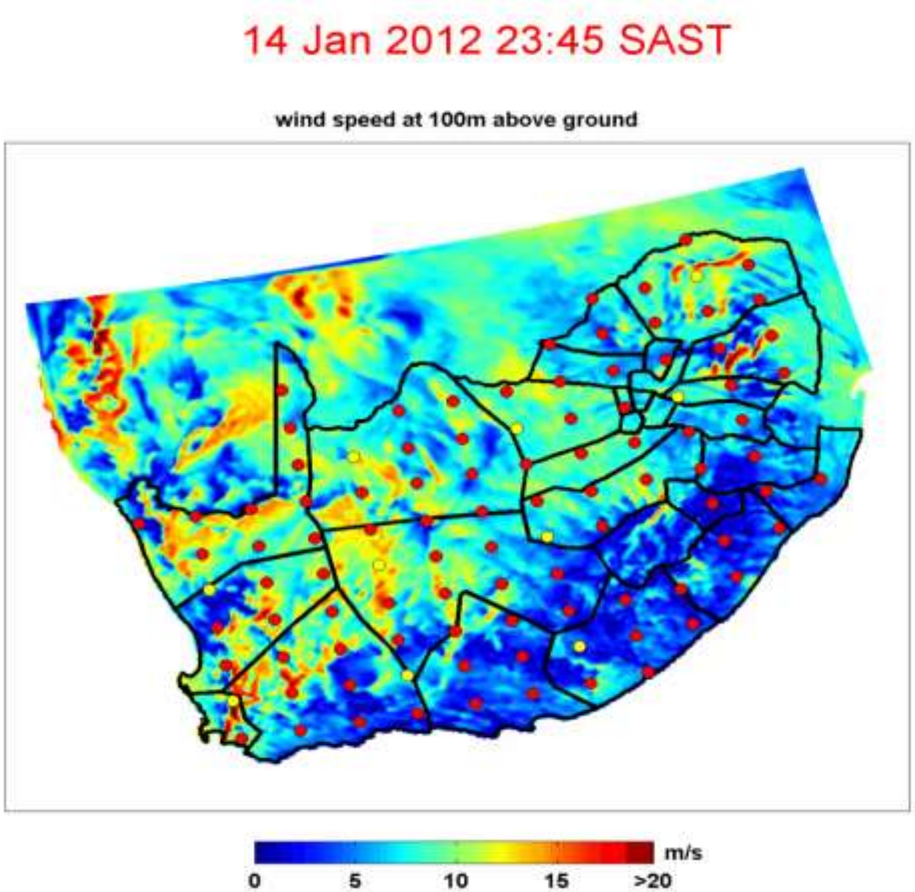
Simulated wind-speed profile and wind power output for 14 January 2012

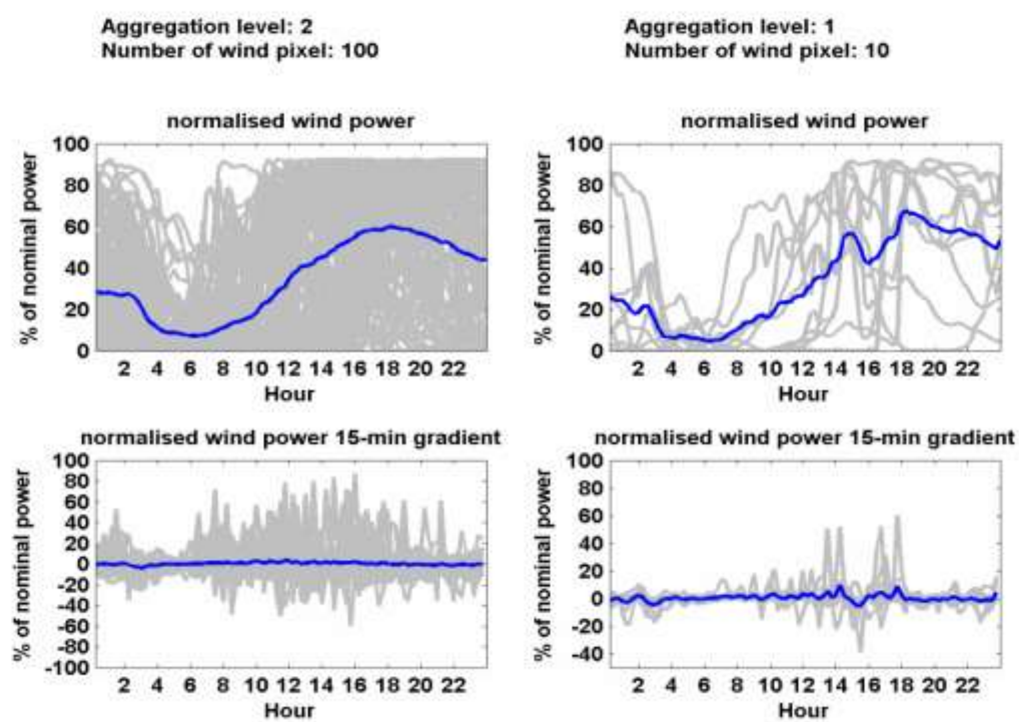


REV 1

Aggregating 100 wind farms: 15-min gradients almost zero

Simulated wind-speed profile and wind power output for 14 January 2012

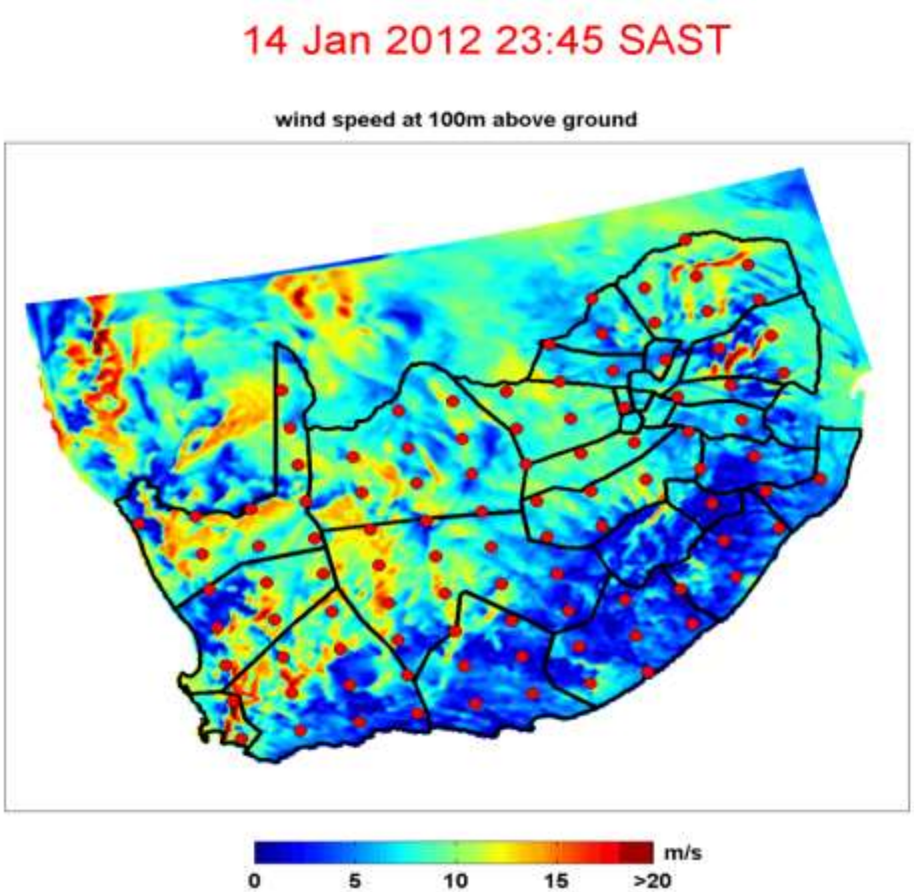


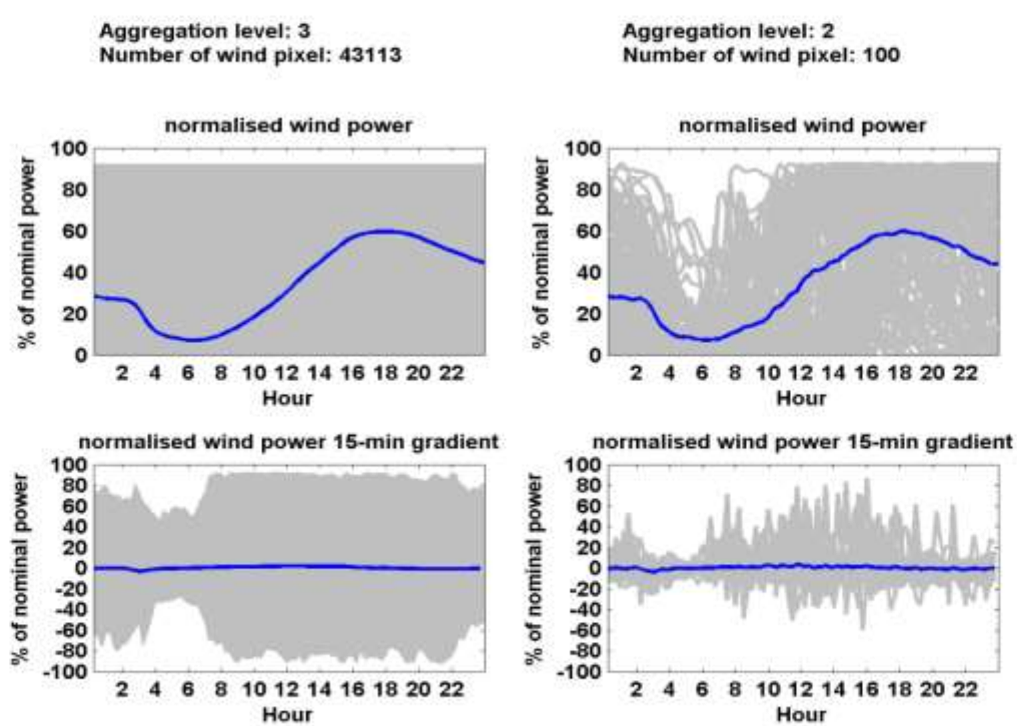


REV 1

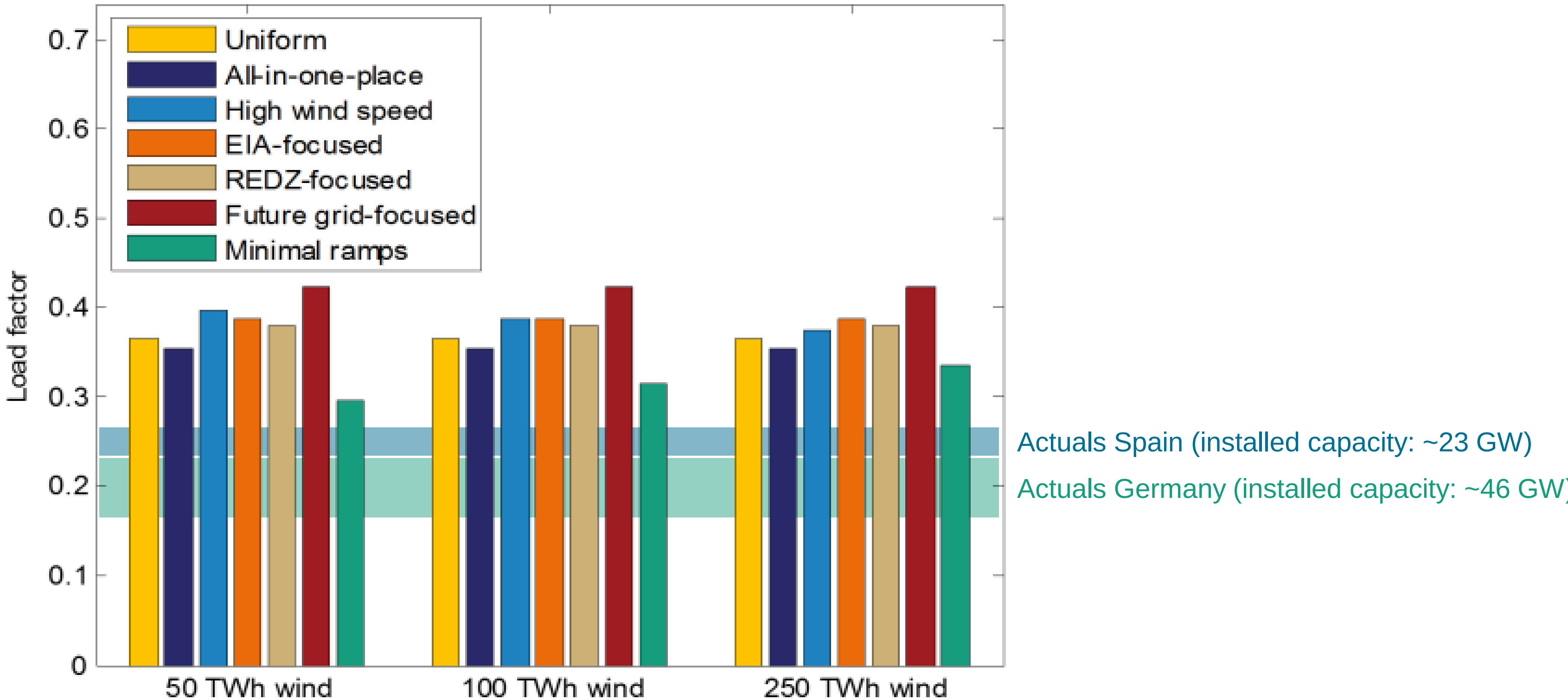
Aggregation across entire country: wind output very smooth

Simulated wind-speed profile and wind power output for 14 January 2012





In all scenarios, achievable load factors are very high



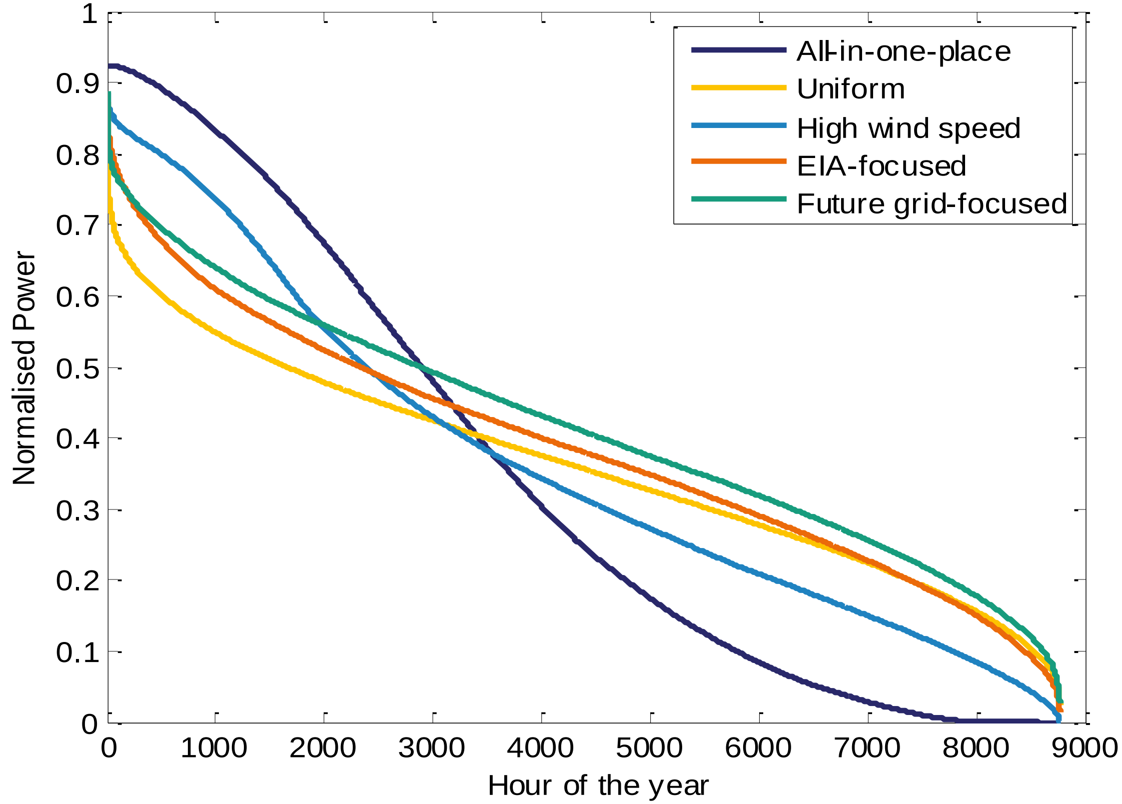
→ Very high load factors for all scenarios

→ „Minimal ramps“ optimization leads to lower ramps but also to lower load factors

REV 1

Wide spatial wind distribution leads to smooth duration curve

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



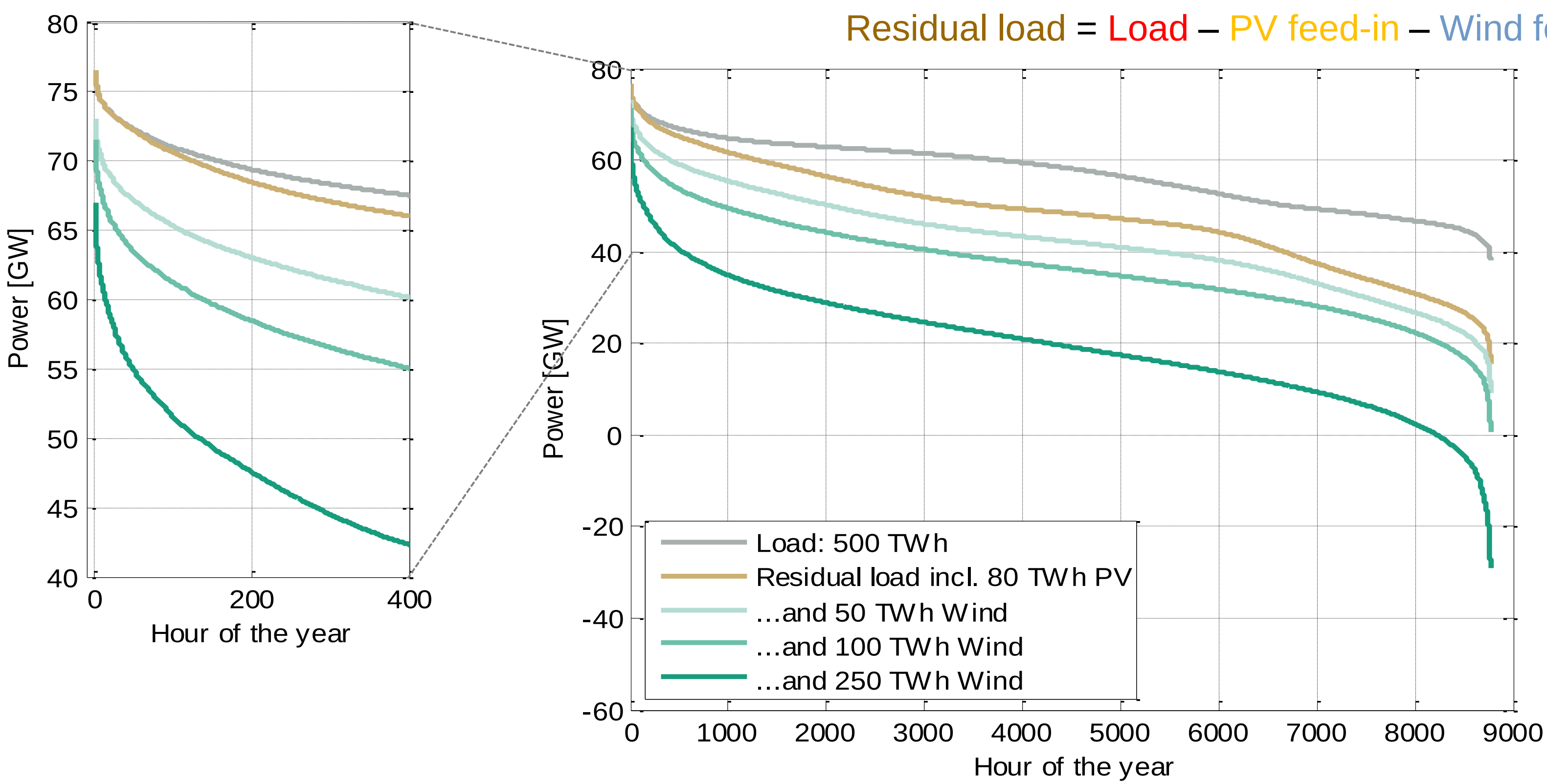
→ Wider distribution leads to smoother wind-power duration curves

→ With a wider distribution there is residual electricity feed-in at all times

REV 1

Excess energy only occurs with very high wind penetration

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



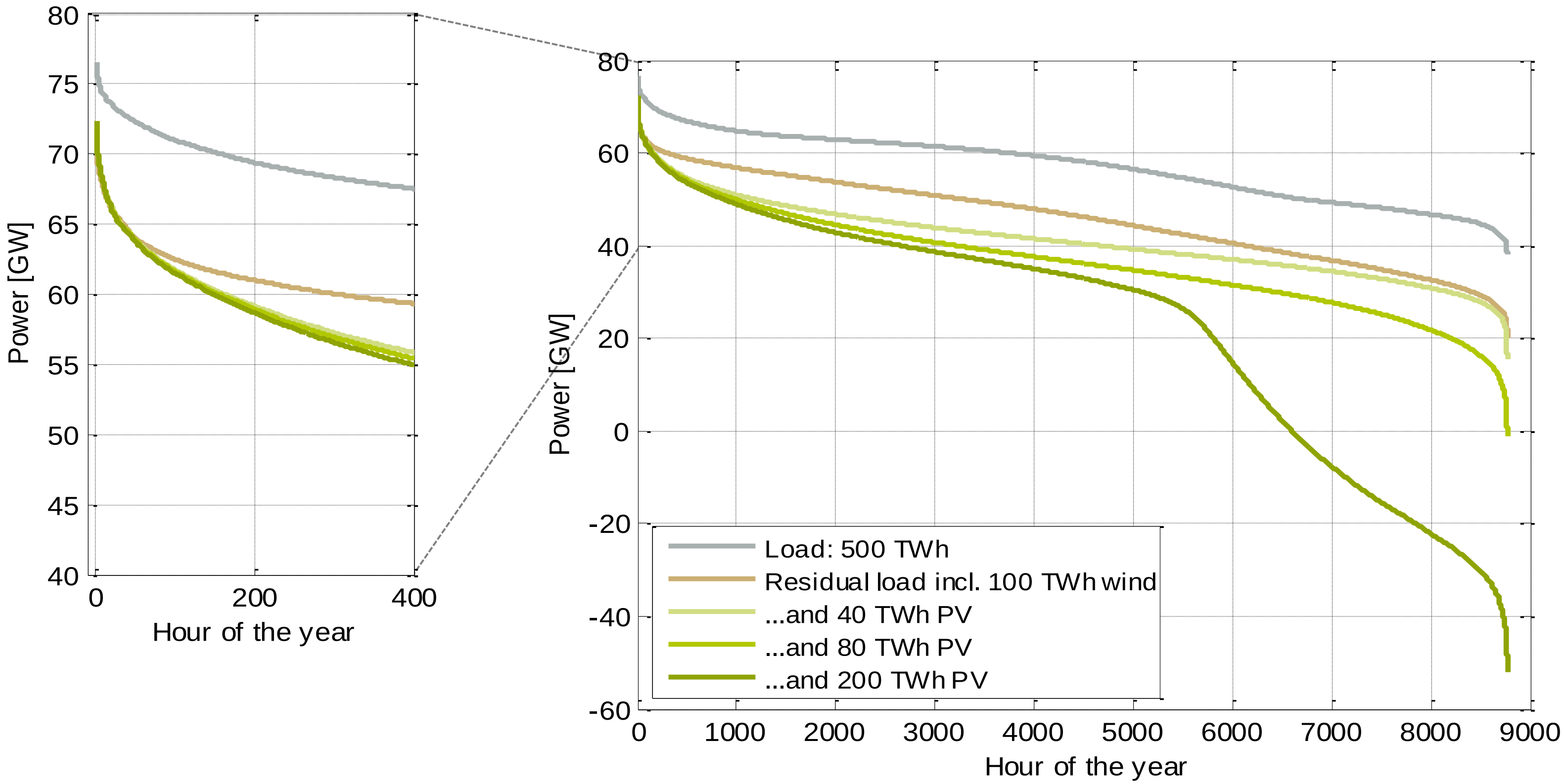
→ Wind feed-in reduces the residual load at almost every moment

→ Electricity surplus occurs at very high wind penetration only

REV 1

Solar PV: excess steeply increases above certain penetration

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



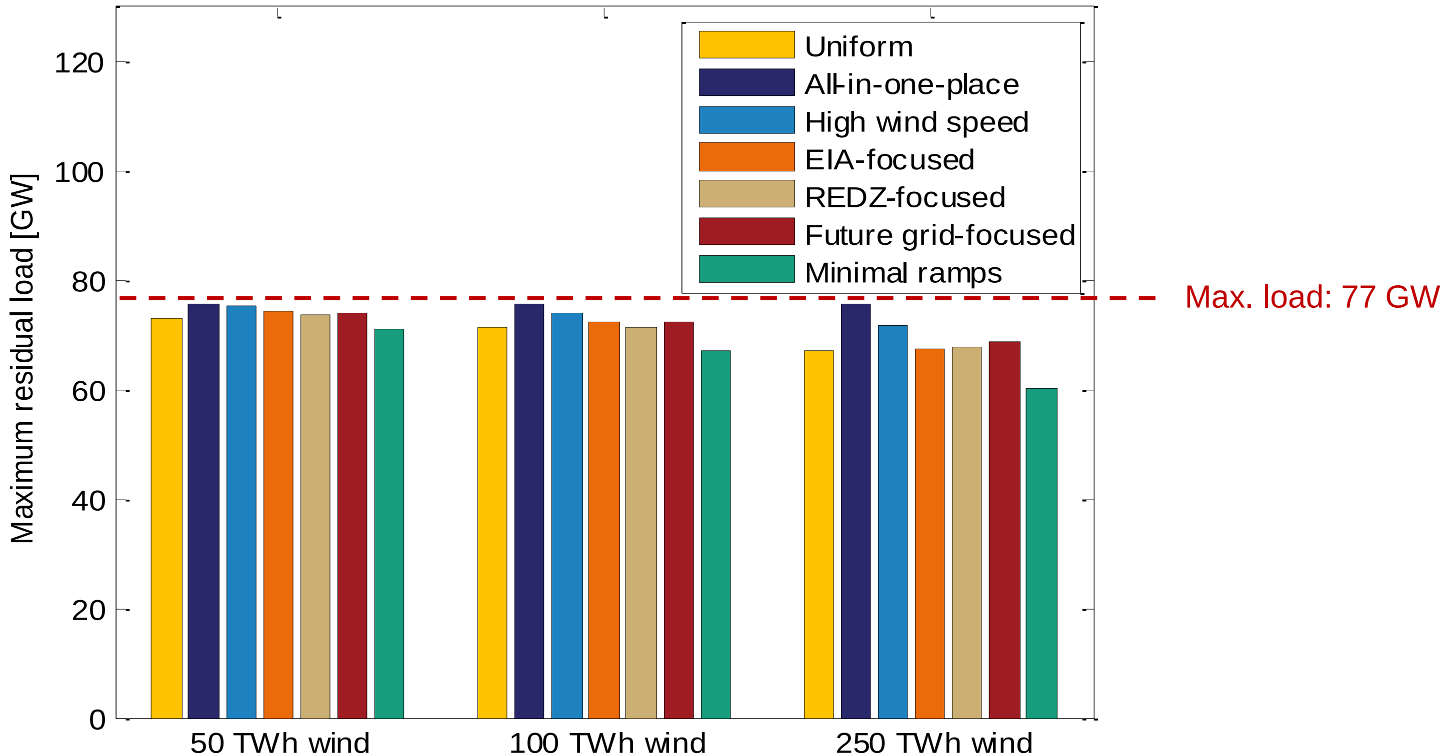
→ High PV shares leads to high electricity surpluses

→ Base load disappears

REV 1

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

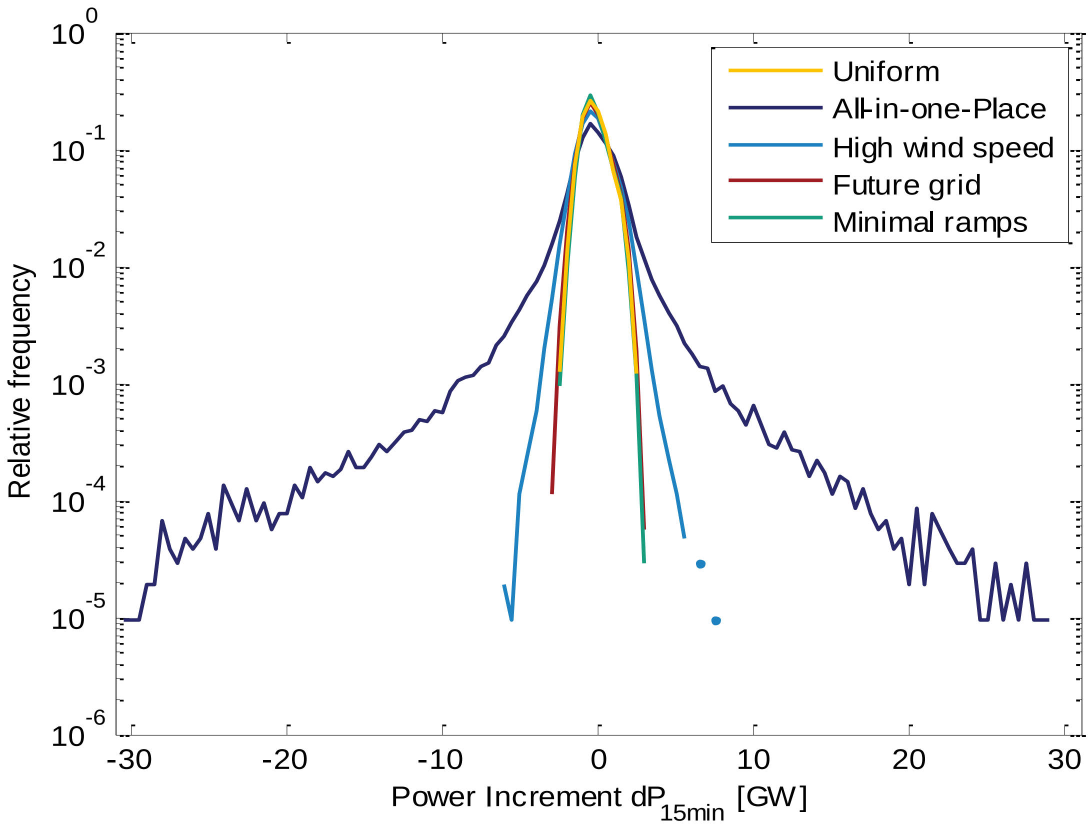
→ Installed capacity of PV does not have an influence

REV 1

Spatial distribution reduces 15-minute gradients drastically

Relative frequency of 15-min gradients of residual load for different wind spatial distribution

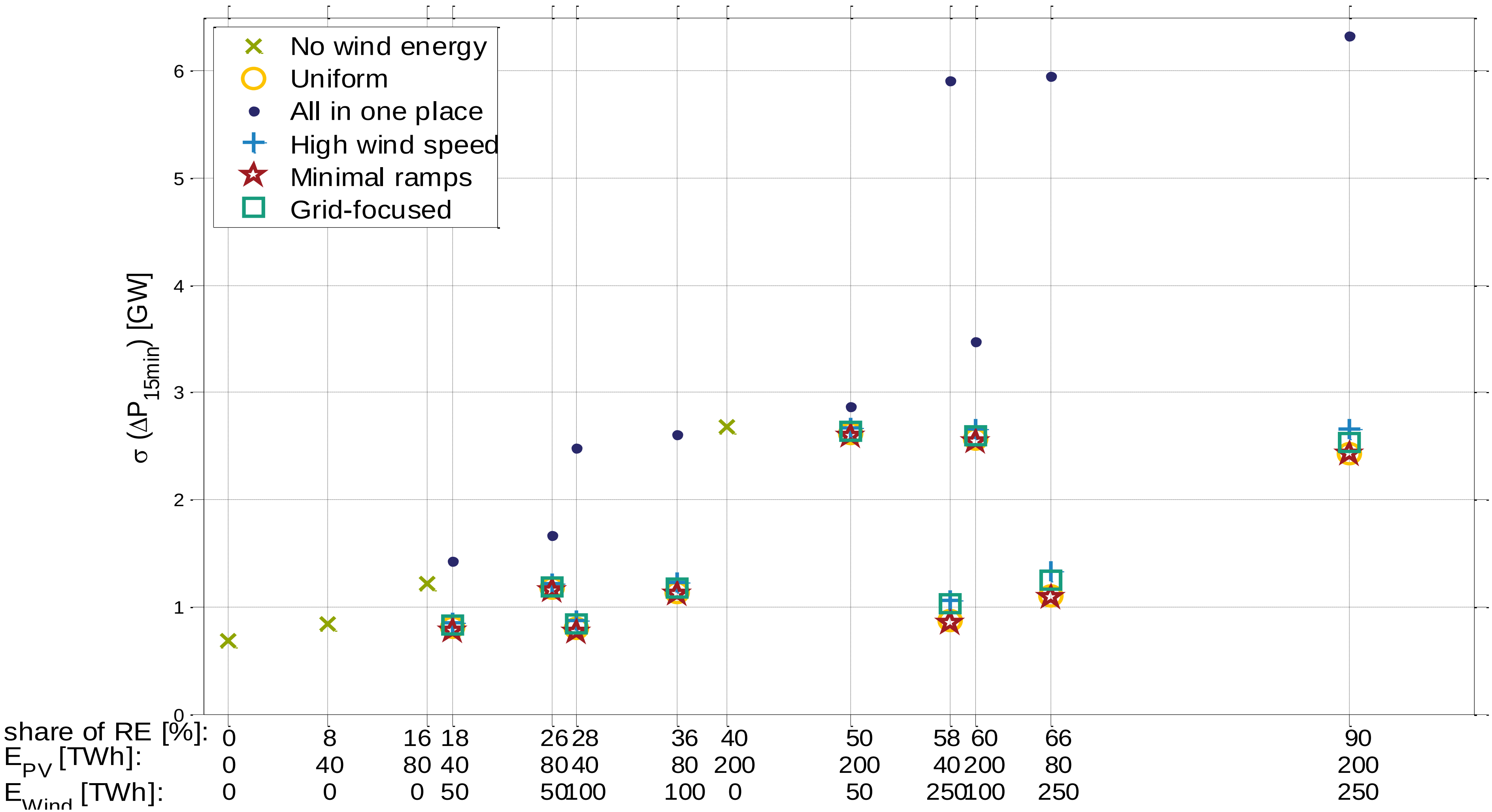
- 100 TWh of electricity from wind energy and 40 TWh from PV



REV 1

Short-term fluctuations of residual load quantified for different penetration with wind and solar PV

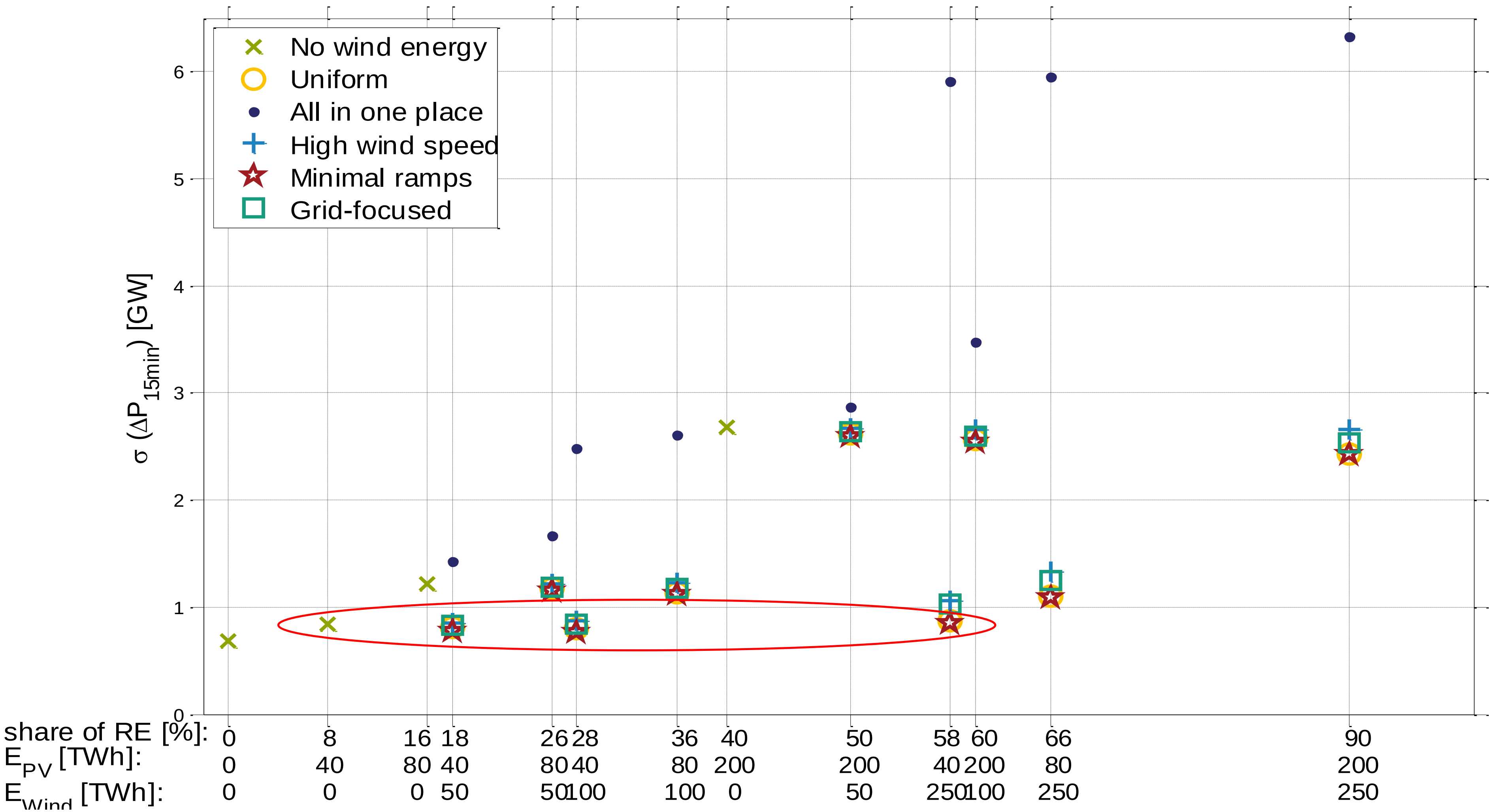
Standard deviation of 15-min gradients of residual load for different wind penetrations and scenarios



REV 1

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



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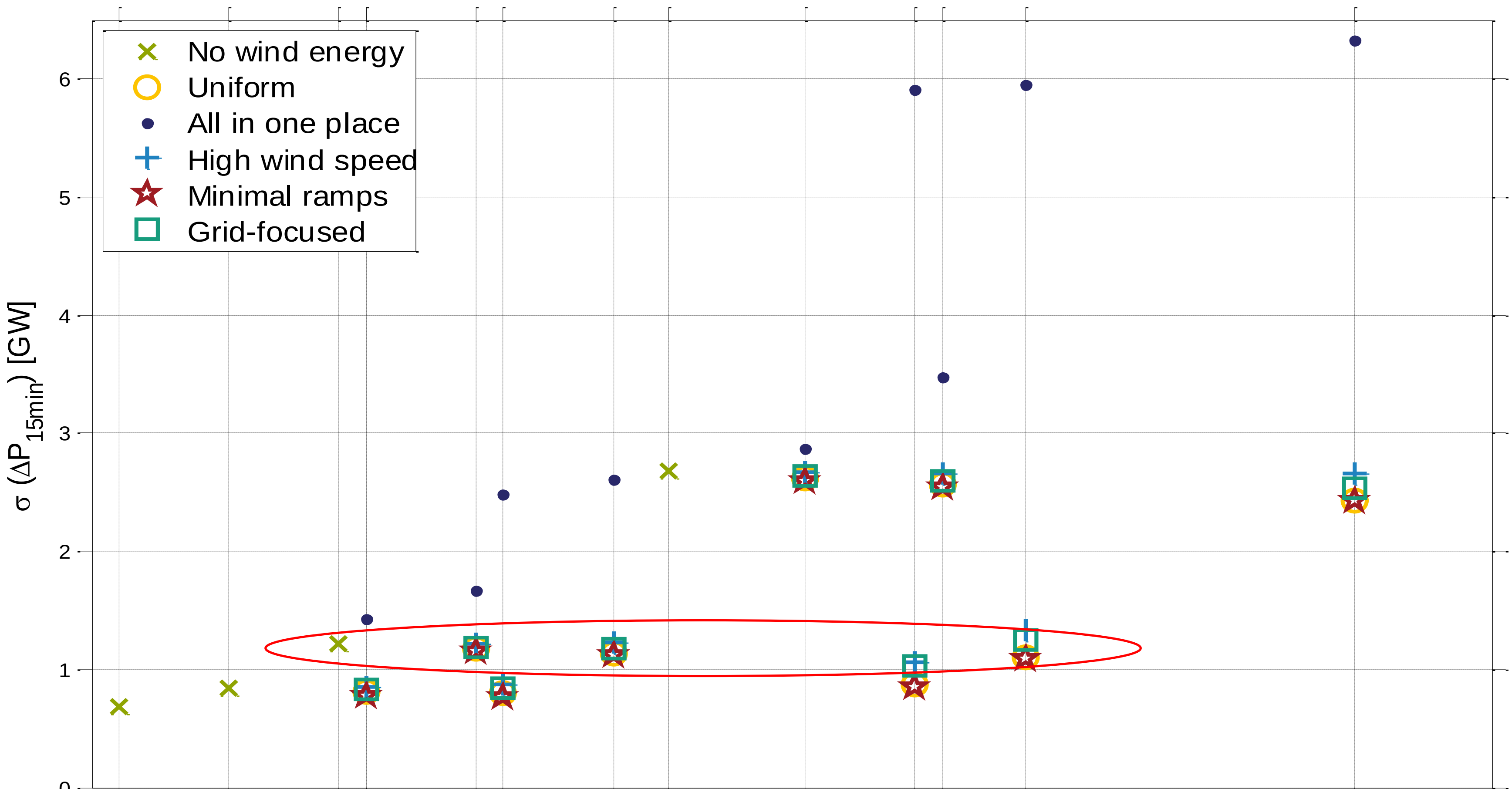
Standard deviation of 15-min gradients of residual load for different wind penetrations and scenarios



share of RE [%]:	0	8	16	18	26	28	36	40	50	58	60	66	90
E_{PV} [TWh]:	0	40	80	40	80	40	80	200	200	40	200	80	200
E_{Wind} [TWh]:	0	0	0	50	50	100	100	0	50	250	100	250	250

REV 1

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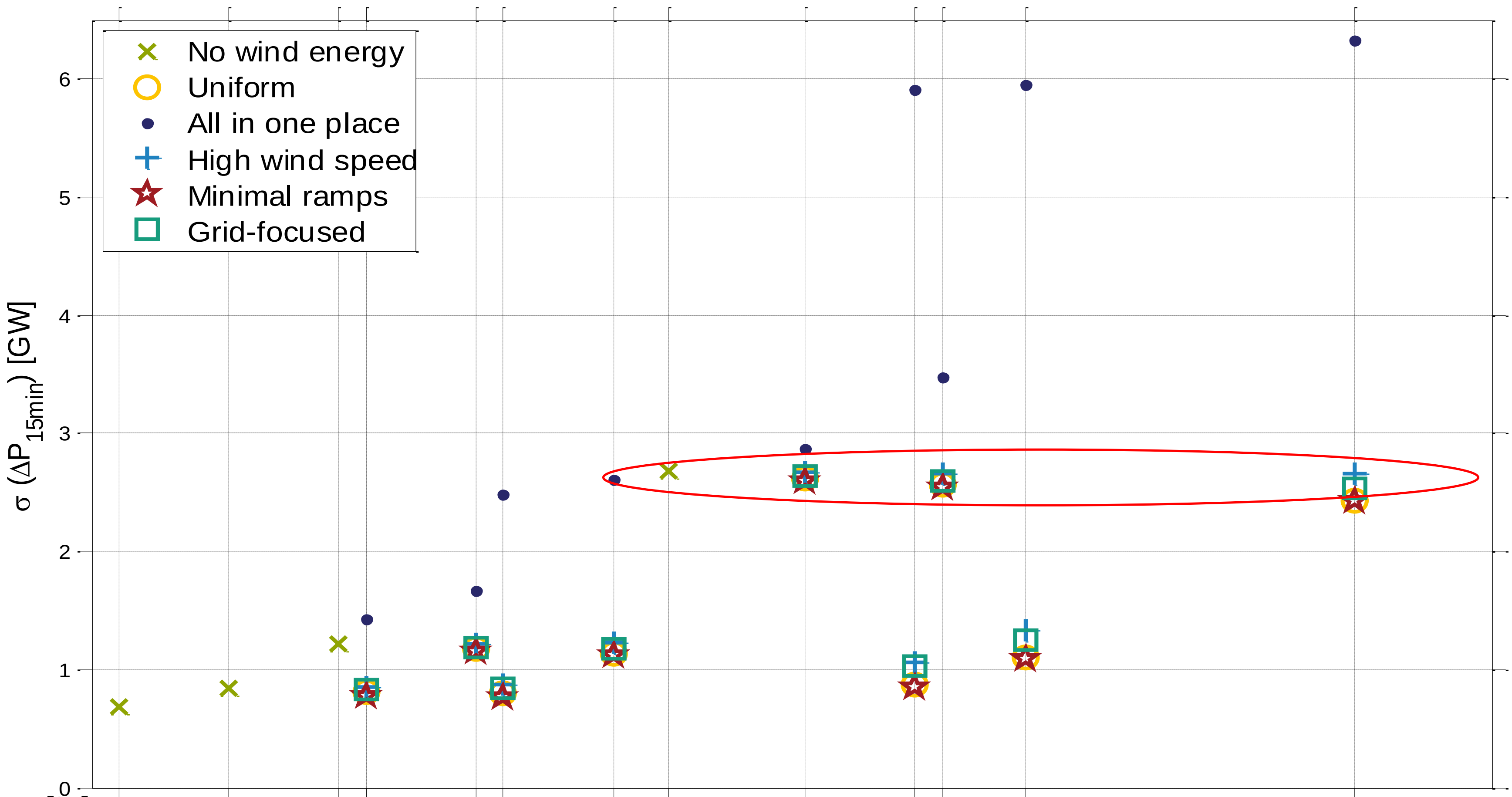
15-min gradients do not increase with higher wind penetration

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



share of RE [%]:	0	8	16	18	26	28	36	40	50	58	60	66	90
E_{PV} [TWh]:	0	40	80	40	80	40	80	200	200	40	200	80	200
E_{Wind} [TWh]:	0	0	0	50	50	100	100	0	50	250	100	250	250

REV 1

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

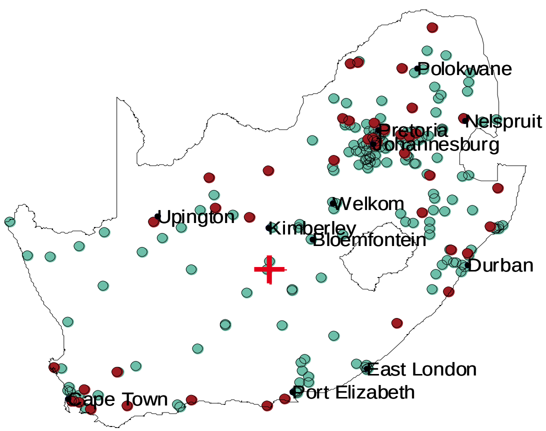
A share of up to ~30% of RE causes no significant increase in 15-minute gradients

Wind alone can provide 50% of the total energy demand without significant increase in the 15-minte gradients; the wind output changes are more low frequency over several hours

REV 1

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

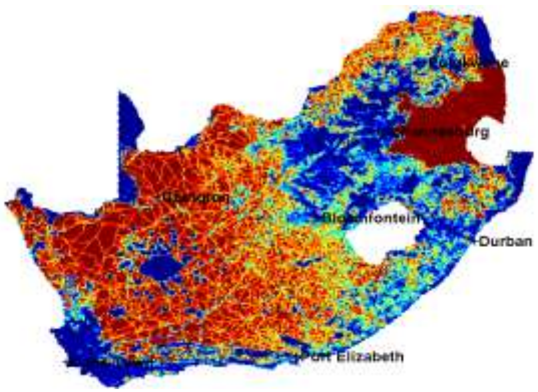


		Potential	50 TWh/yr	100 TWh/yr	250 TWh/yr	All in one place 100 TWh/yr
Capacity		0.16 GW	16 GW	32 GW	81 GW	32 GW
Minimum output		0 GW	0 GW	0 GW	0 GW	0 GW
Normalised wind power 15-min gradient	Max	92%	92%	92%	92%	92%
	Min	-91%	-91%	-91%	-91%	-91%
Residual load 15-min gradient	Max	5.5 GW	15 GW	30 GW	74 GW	30 GW
	Min	-3.1 GW	-15 GW	-30 GW	-74 GW	-30 GW
Daily energy	Max	3.5 GWh	354 GWh	708 GWh	1 769 GWh	708 GWh
	Mean	1.3 GWh	137 GWh	274 GWh	685 GWh	274 GWh
	Min	0 GWh	0.5 GWh	1.0 GWh	2.5 GWh	1 GWh

REV 1

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

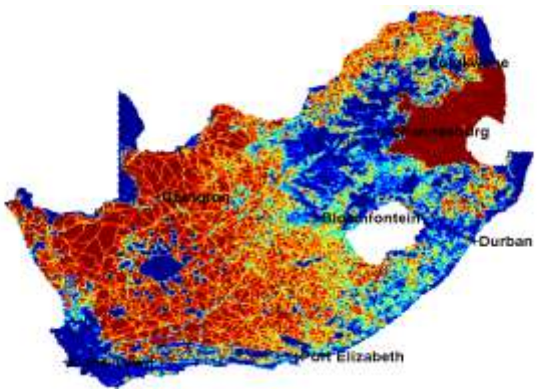


		Potential	50 TWh/yr	100 TWh/yr	250 TWh/yr	All in one place 100 TWh/yr
Capacity		6 787 GW	16 GW	31 GW	78 GW	32 GW
Minimum output		162 GW	0.4 GW	0.8 GW	1.9 GW	0 GW
Normalised wind power 15-min gradient	Max	4.2%	4.2%	4.2%	4.2%	92%
	Min	-4.3%	-4.3%	-4.3 %	-4.3 %	-90%
Residual load 15-min gradient	Max	291 GW	5.4 GW	5.3 GW	4.7 GW	30 GW
	Min	-285 GW	-3.2 GW	-3.3 GW	-3.6 GW	-30 GW
Daily energy	Max	119 449 GWh	274 GWh	549 GWh	1 374 GWh	708 GWh
	Mean	59 494 GWh	137 GWh	274 GWh	685 GWh	274 GWh
	Min	13 327 GWh	31 GWh	61 GWh	153 GWh	1 GWh

REV 1

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

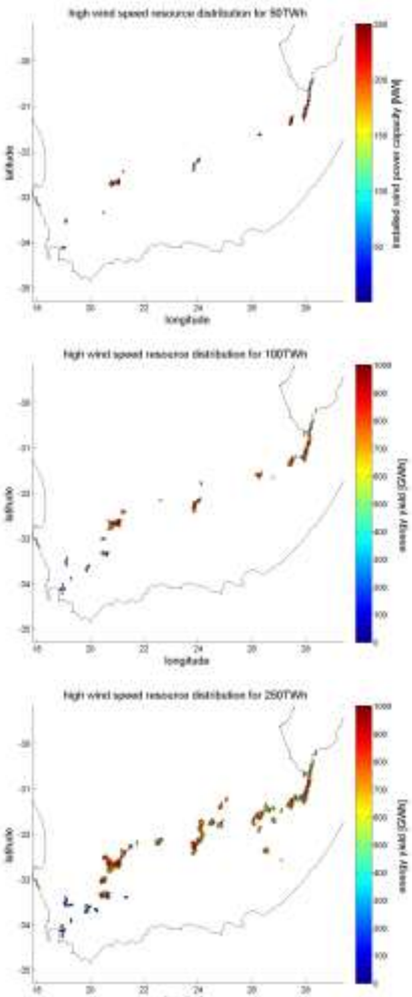


		Potential	50 TWh/yr	100 TWh/yr	250 TWh/yr	All in one place 100 TWh/yr
Capacity		6 787 GW	16 GW	31 GW	78 GW	32 GW
Minimum output		162 GW	0.4 GW	0.8 GW	1.9 GW	0 GW
Normalised wind power 15-min gradient						
Residual load 15-min gradient						
Daily energy						
	Mean	59 494 GWh	137 GWh	274 GWh	685 GWh	274 GWh
	Min	13 327 GWh	31 GWh	61 GWh	1 534 GWh	1 GWh

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

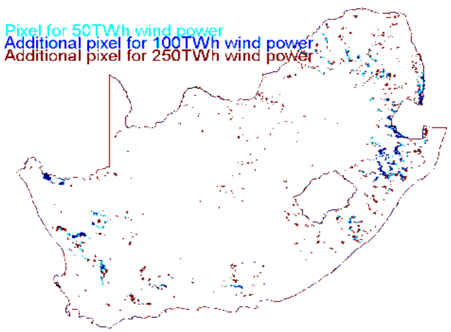


		Potential	50 TWh/yr	100 TWh/yr	250 TWh/yr	All in one place 100 TWh/yr
Capacity		6 787 GW	15 GW	30 GW	76 GW	32 GW
Minimum output		162 GW	0.01 GW	0.04 GW	0.08 GW	0 GW
Normalised wind power 15-min gradient	Max	4.2%	16%	12%	8.4%	92%
	Min	-4.3%	-17%	-12%	-8.5%	-91%
Residual load 15-min gradients	Max	292 GW	5.4 GW	5.9 GW	9.0 GW	30 GW
	Min	-286 GW	-3.3 GW	-4.3 GW	-5.7 GW	-30 GW
Daily energy	Max	119 450 GWh	301 GWh	603 GWh	1 539 GWh	708 GWh
	Mean	59 494 GWh	138 GWh	275 GWh	686 GWh	274 GWh
	Min	13 327 GWh	2.9 GWh	6.7 GWh	15 GWh	1 GWh

REV 1

Wind turbine distribution to reduce 15-min-ramps: +/- 4%

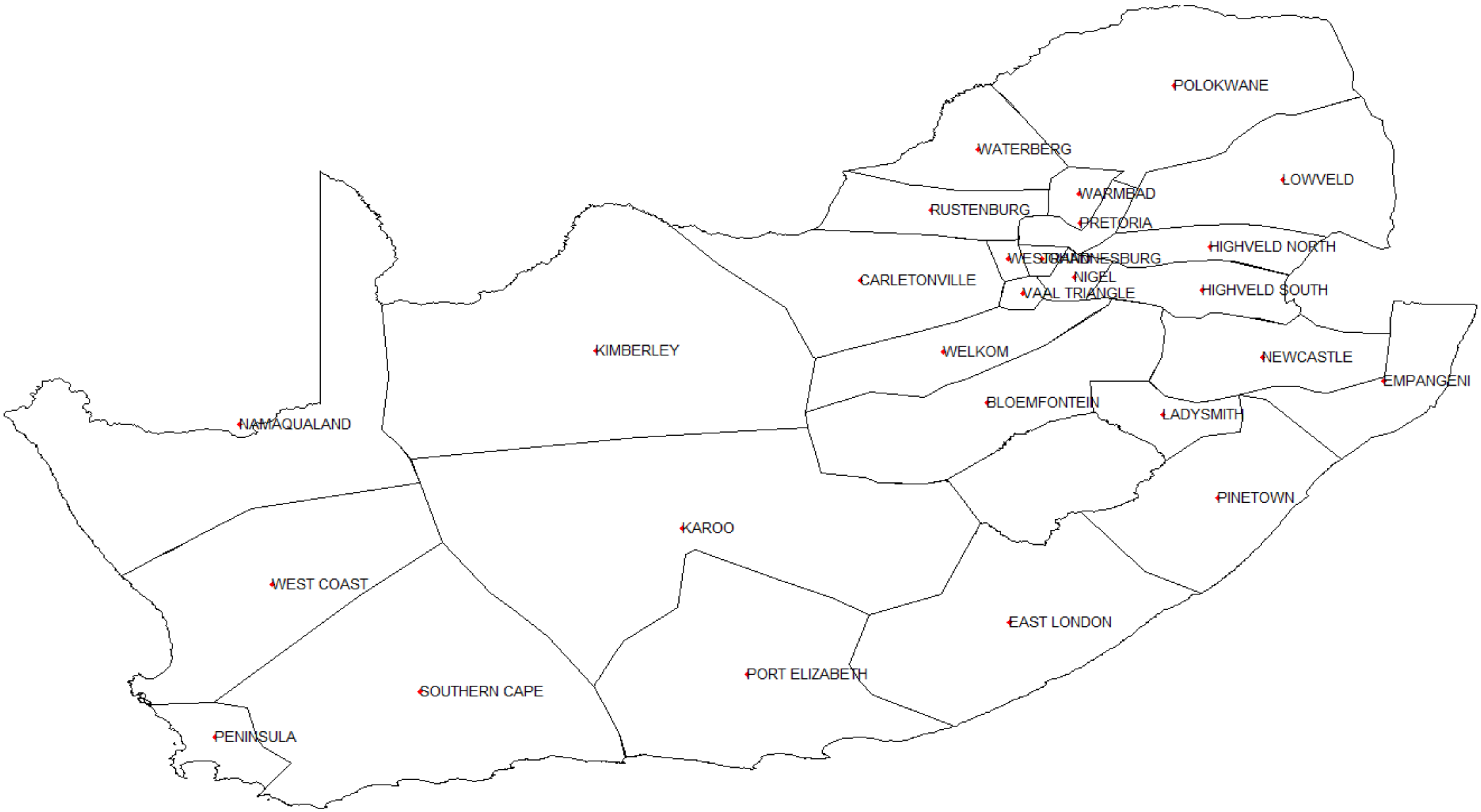
Statistics of aggregated wind output and residual load for the “minimum gradients” wind distribution



		Potential	50 TWh/yr	100 TWh/yr	250 TWh/yr	All in one place 100 TWh/yr
Capacity		6 787 GW	17 GW	33 GW	82 GW	32 GW
Minimum output		162 GW	0.04 GW	0.16 GW	2.5 GW	0 GW
Normalised wind power 15-min gradient	Max	4.2%	10%	7.7%	4.5%	92%
	Min	-4.3%	-7.2%	-4.6%	-3.8%	-91%
Residual load 15-min gradient	Max	292 GW	5.2 GW	5.0 GW	4.6 GW	30 GW
	Min	-286 GW	-3.0 GW	-2.9 GW	-3.3 GW	-30 GW
Daily energy	Max	119 450 GWh	265 GWh	499 GWh	1 198 GWh	708 GWh
	Mean	59 494 GWh	137 GWh	274 GWh	685 GWh	274 GWh
	Min	13 327 GWh	32 GWh	84 GWh	247 GWh	1 GWh

REV 1

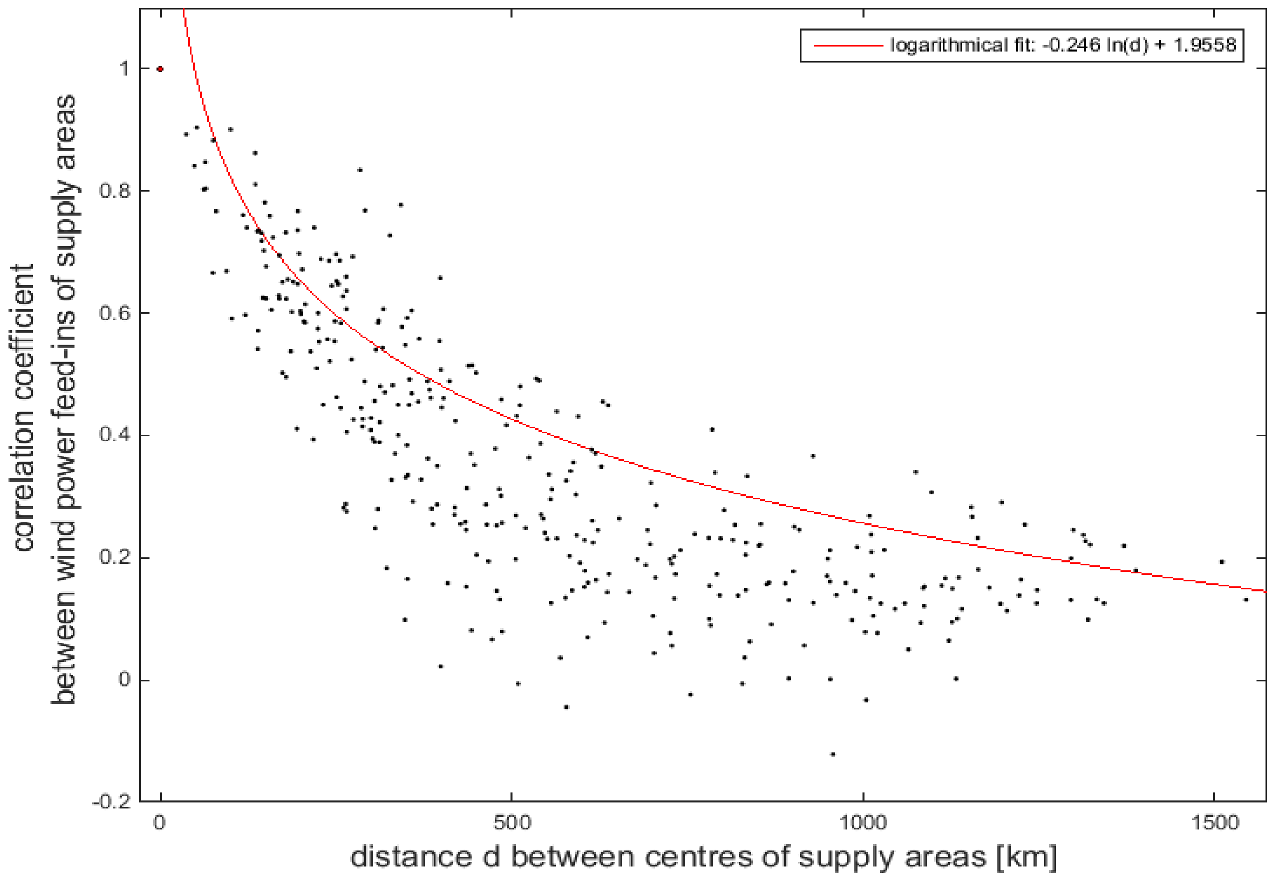
South Africa is split into 27 supply areas – midpoints of these areas are used to measure distance and wind correlation



REV 1

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

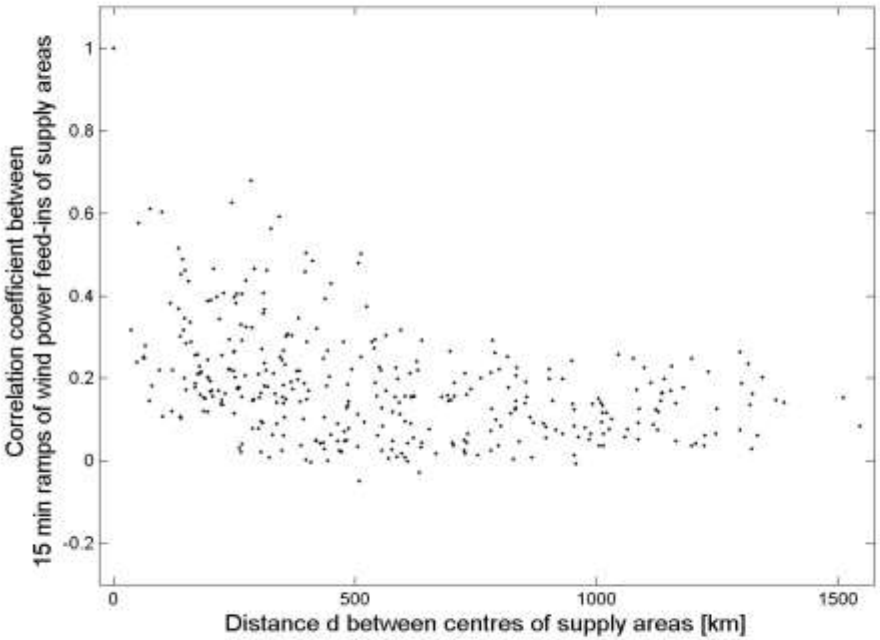


REV 1

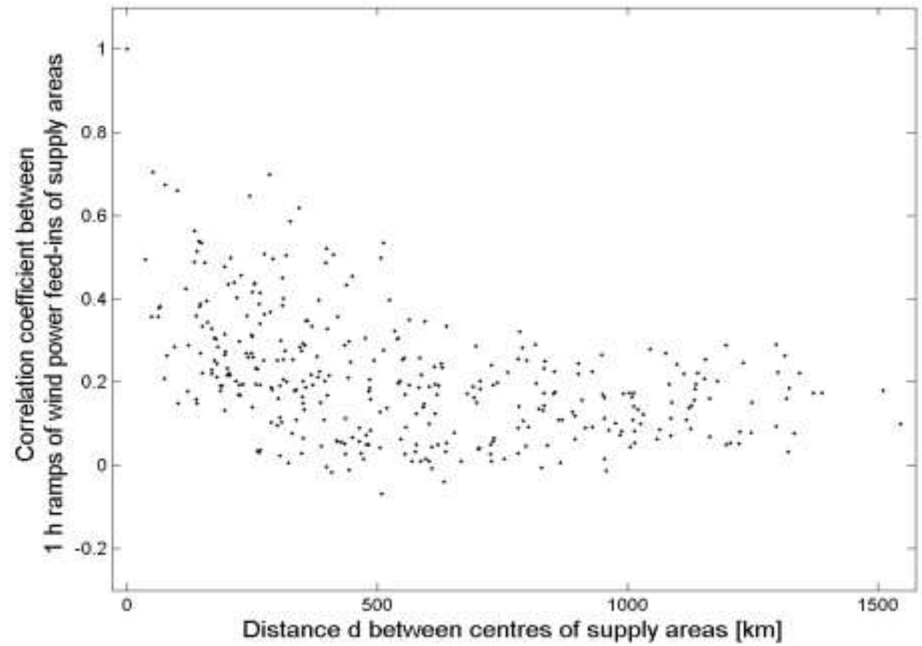
Correlation of wind-power gradients is low for far distances

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

15 minutes gradients

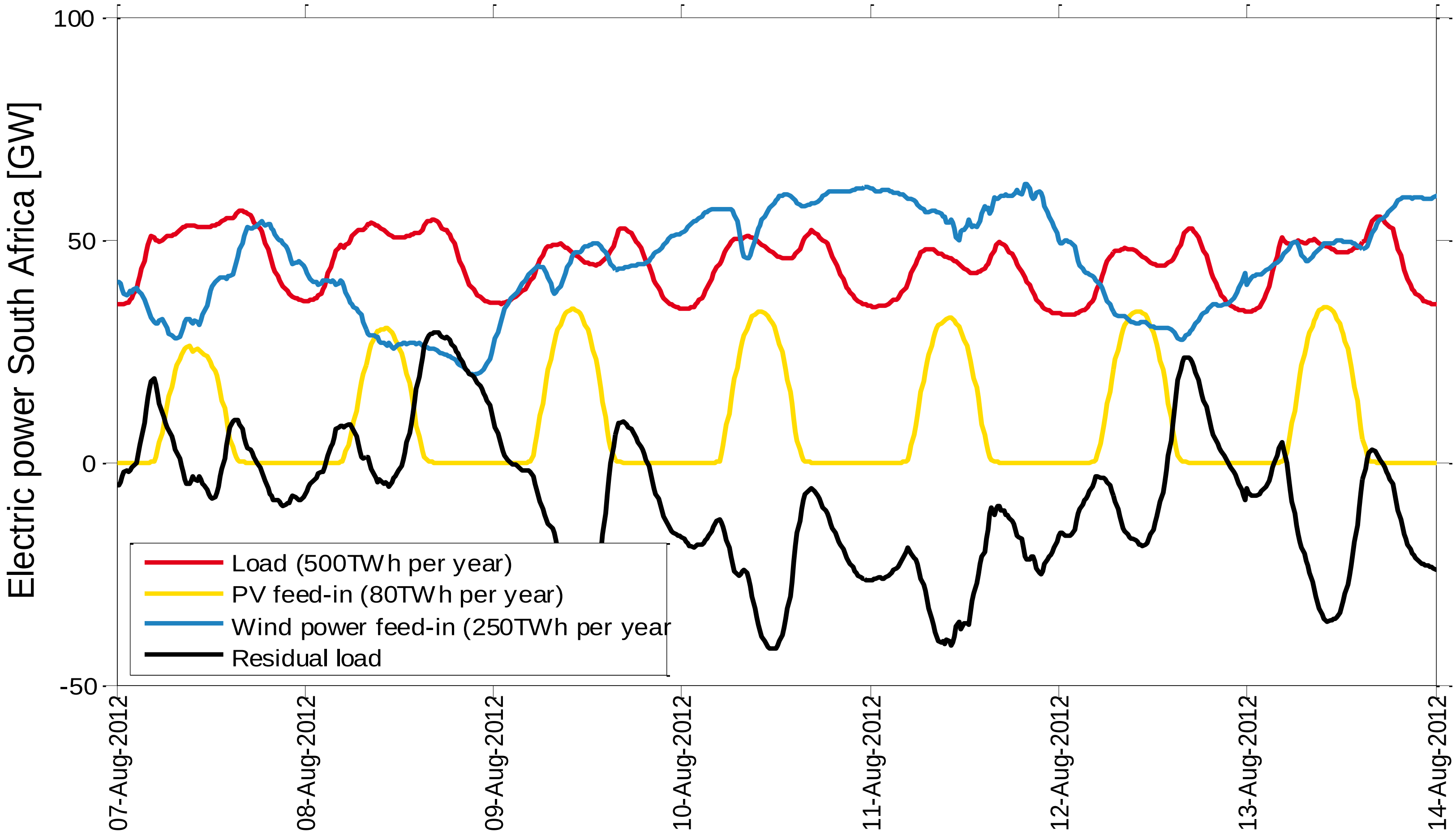


1 hour gradients



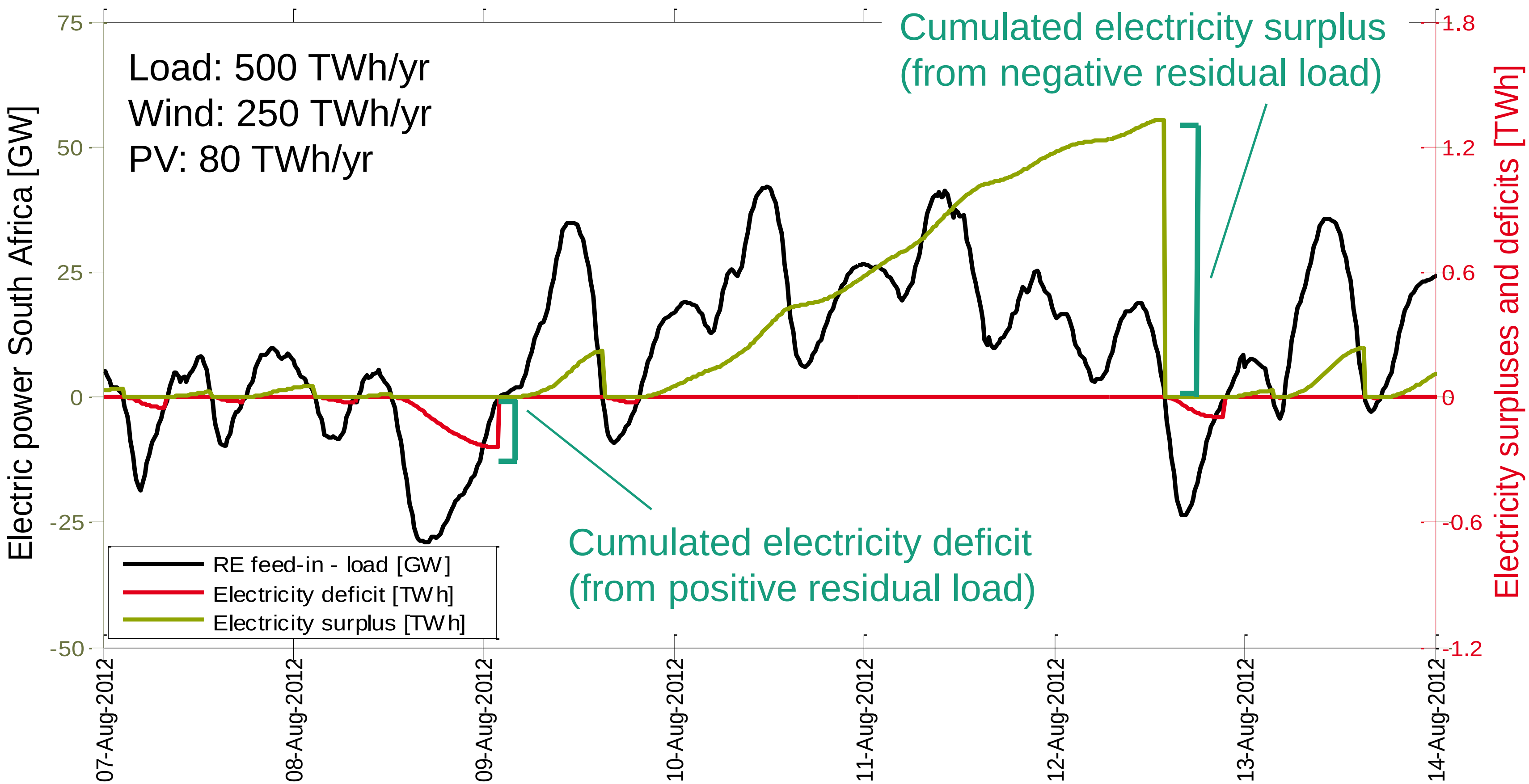
REV 1

Very high wind penetration (250 wind at 500 TWh/yr load): at times, electricity surpluses will occur (negative residual load)



REV 1

The total amount of energy during periods of excess electricity gives an indication for bulk storage needs

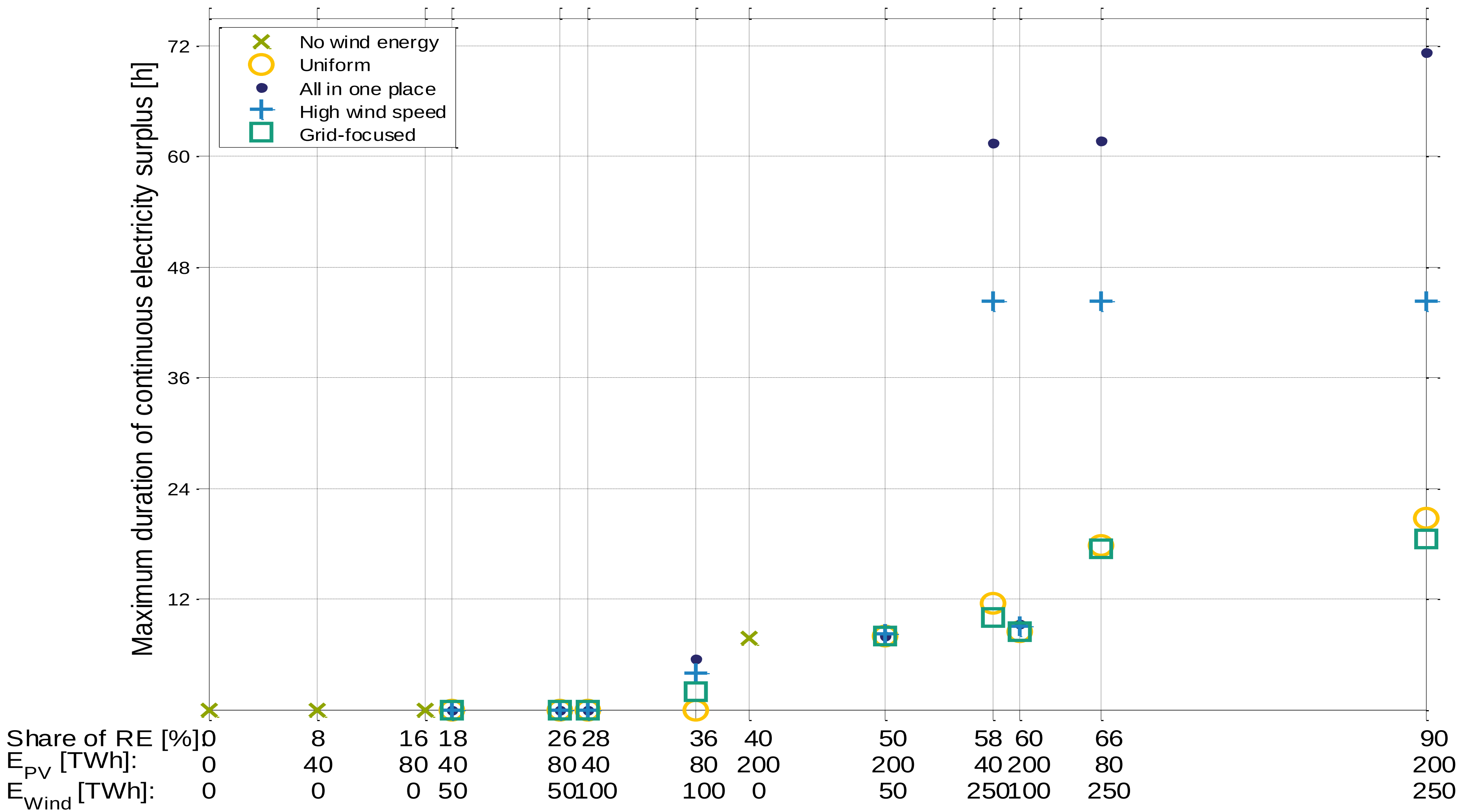


- Electricity deficit can be provided by conventional or flexible power fleet
- Electricity surplus can either be curtailed or stored
- Longest period of continuous excess generation: 18-60 hours, depending on the spatial distribution of the wind fleet

REV 1

Depending on the scenario, between 18-72 hours of continuous excess electricity can occur

Electricity surpluses: Maximum duration by scenario

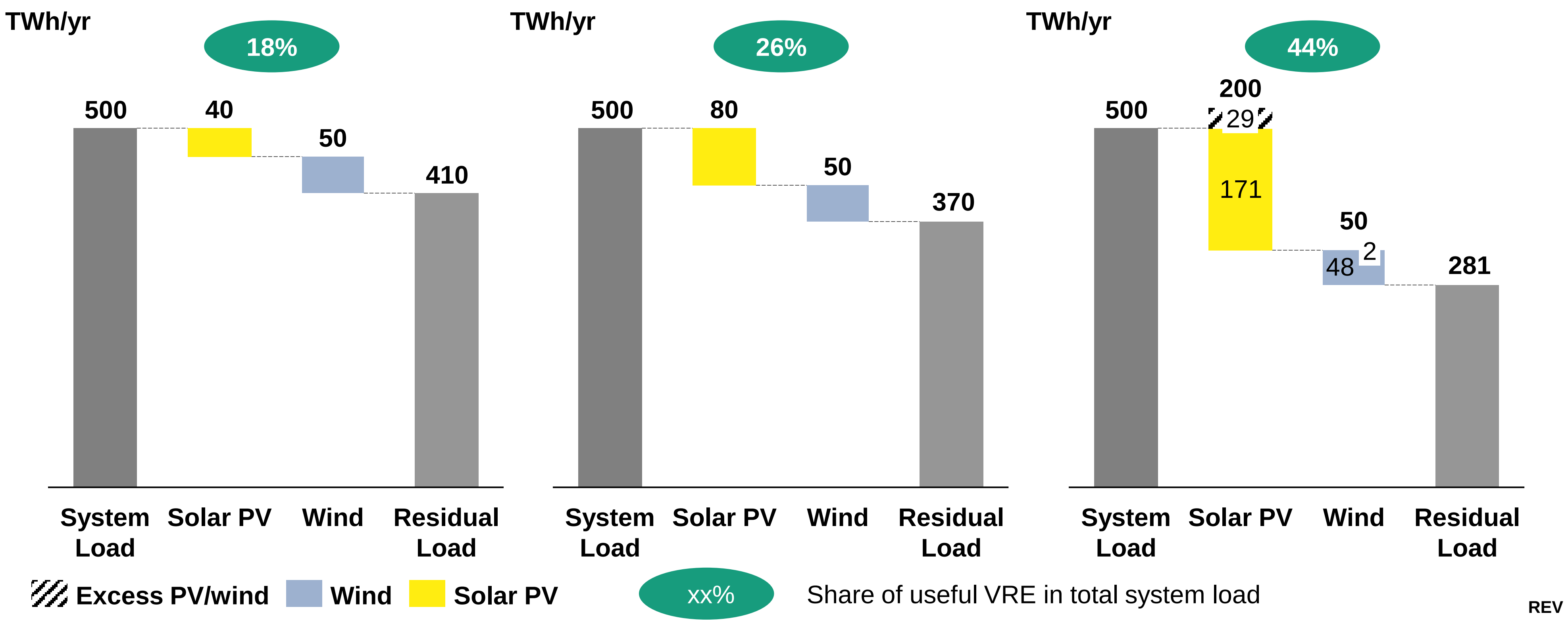


REV 1

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	Medium PV / low wind	High PV / low wind
Load: 500 TWh/yr	Load: 500 TWh/yr	Load: 500 TWh/yr
PV: 40 TWh/yr	PV: 80 TWh/yr	PV: 200 TWh/yr
Wind: 50 TWh/yr	Wind: 50 TWh/yr	Wind: 50 TWh/yr



REV 1

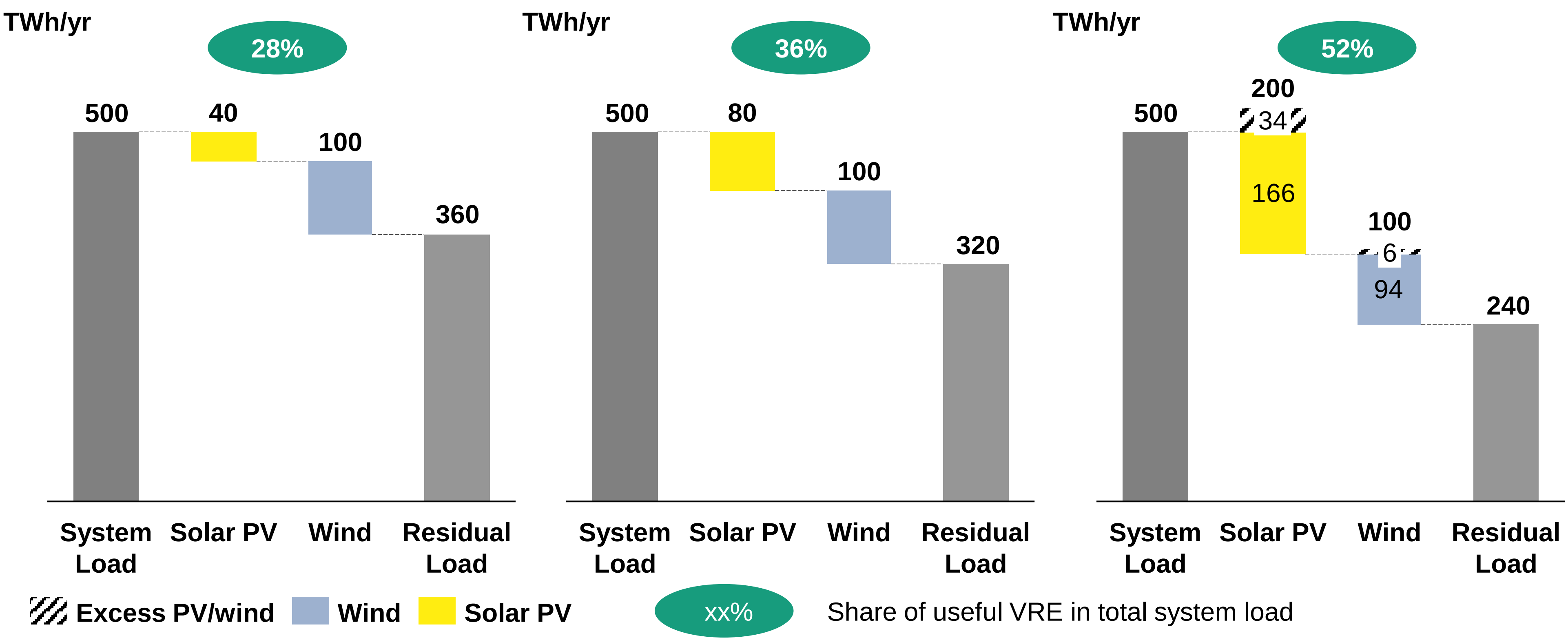
2x wind (50 to 100 TWh/yr): almost no effect on excess energy

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



REV 1

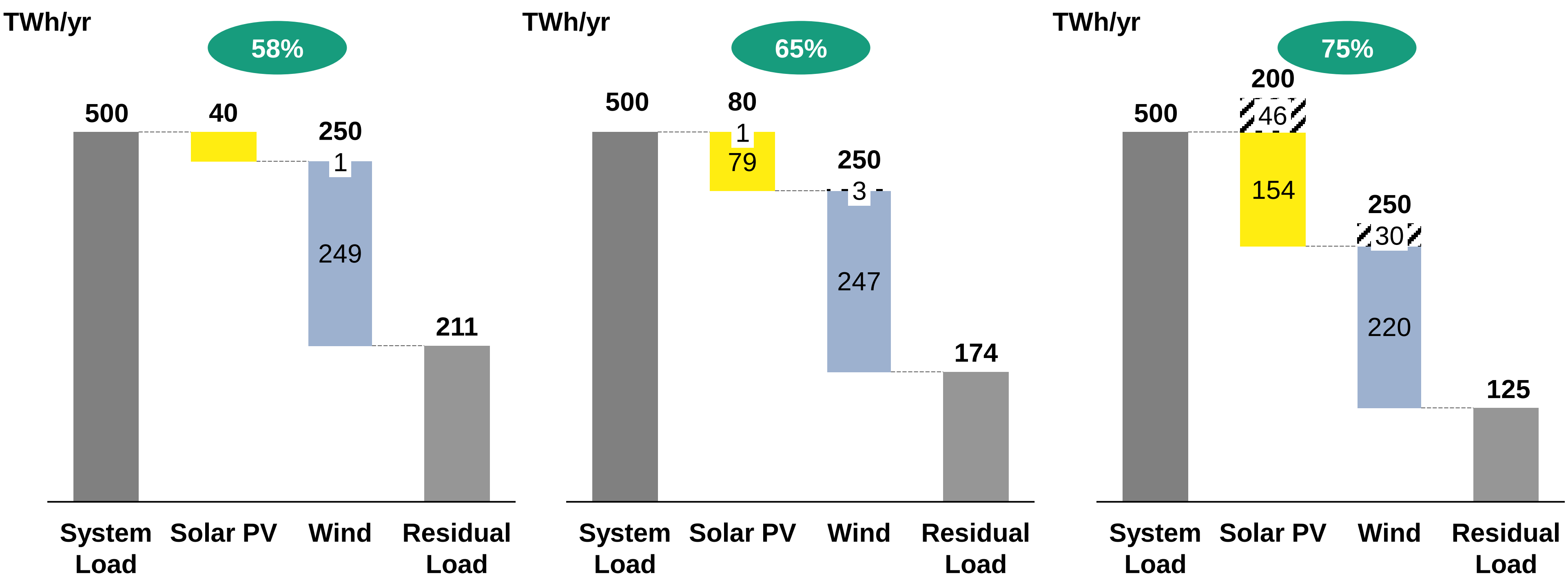
65% VRE share achievable with almost no excess energy

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



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

REV 1

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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

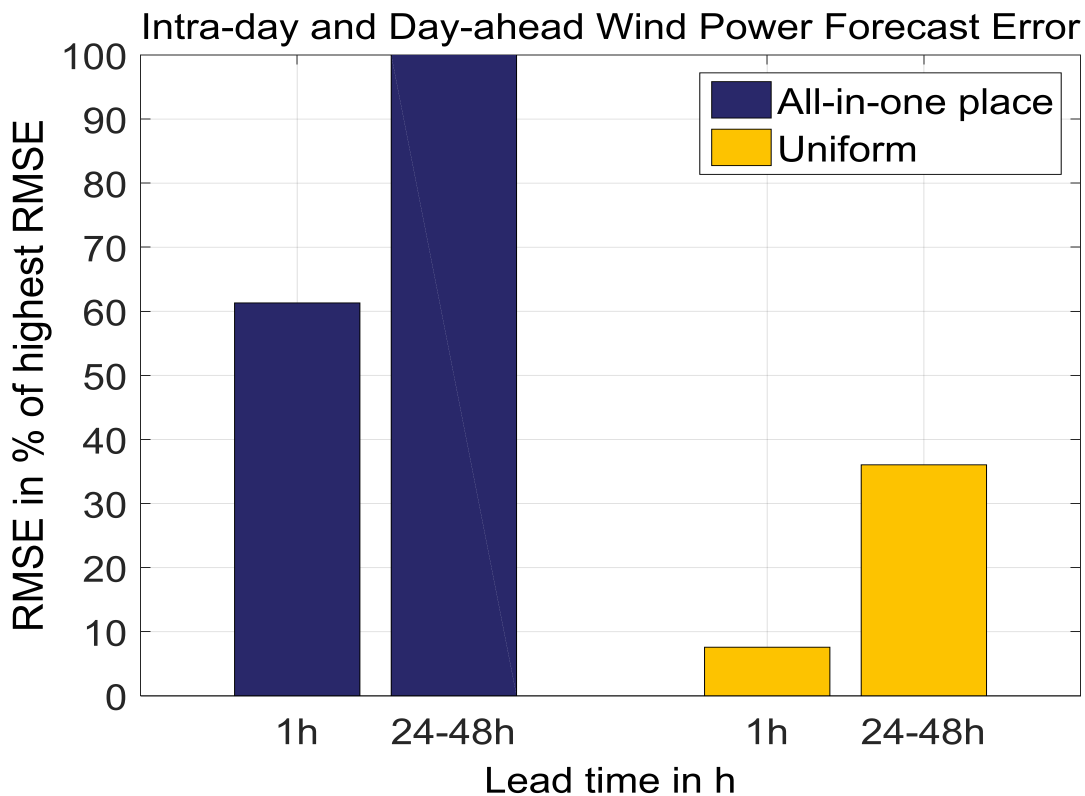
- Up to a certain energy share, solar PV does not cause excess electricity
- Beyond a threshold, solar PV causes large amounts of excess electricity because of the skewed supply pattern of solar PV (daytime only)
- Wind supply is more volatile, but on average better distributed over the full 24 hours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



REV 1

Methodology to derive relative LCOE per pixel

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

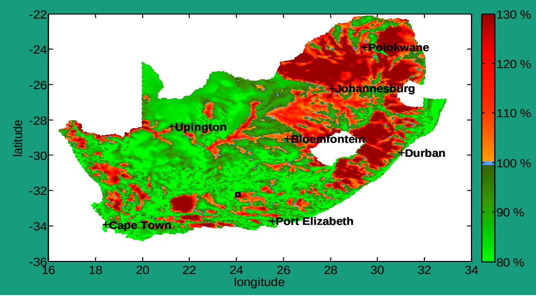
Capex: 80% of overall costs
→ LCOE of turbine type 5 is approximately 20% higher than turbine type 1 (for the same load factor)

Map of relative LCOE (for the same load factor)

Reference pixel
Turbine 1, load factor ~30%

For every pixel: determine load factor multiplier

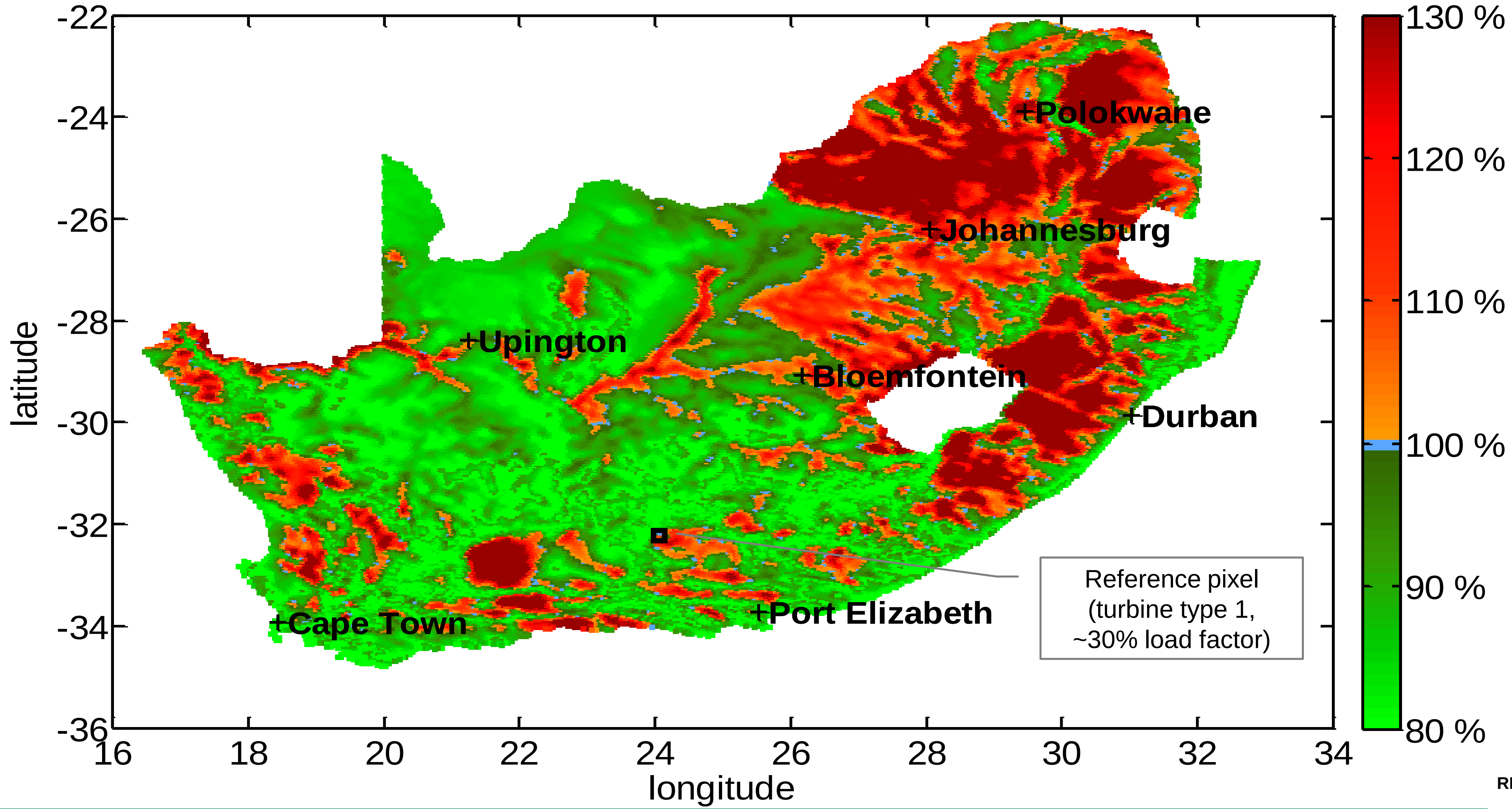
Relative LCOE by multiplying costs with scaled load factors



REV 1

Large parts of RSA can achieve LCOE well below reference

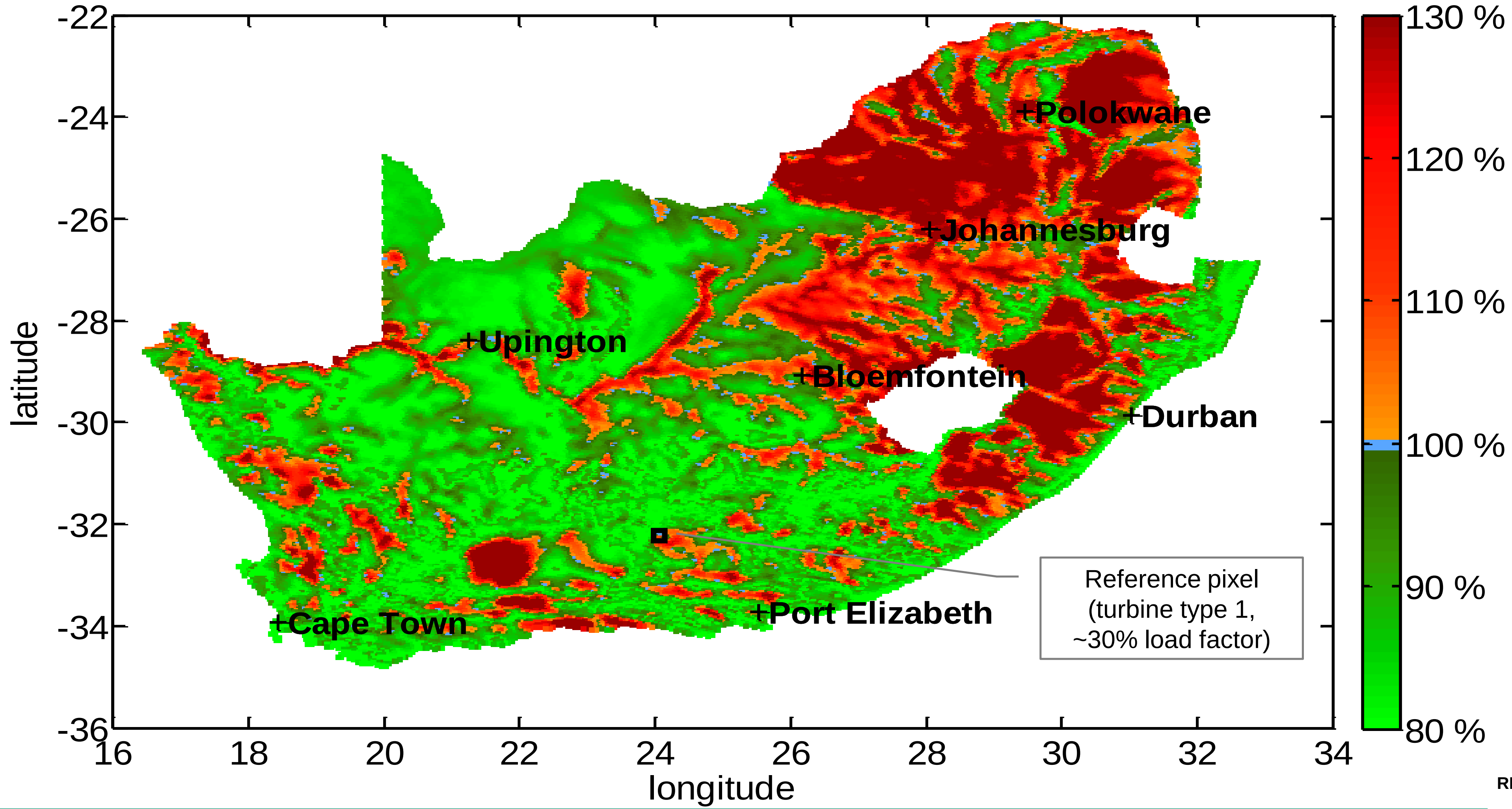
Relative LCOE across South Africa when installing turbine types 1 to 5



REV 1

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)



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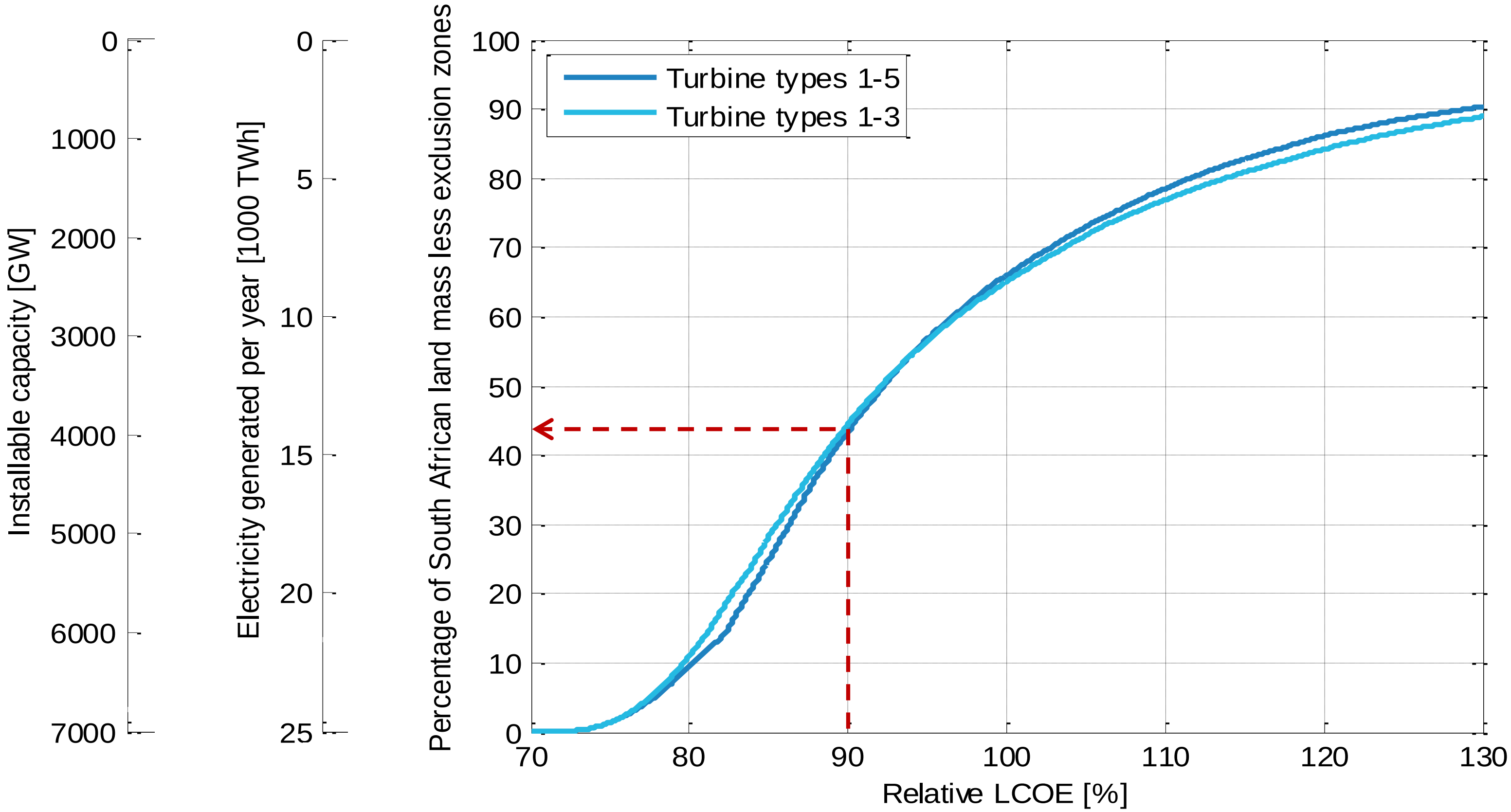
Large parts of the South African suitable land (entire land mass less exclusion zones) can achieve low wind LCOEs



→ 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

REV 1

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)

REV 1

Contents

REV 1

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

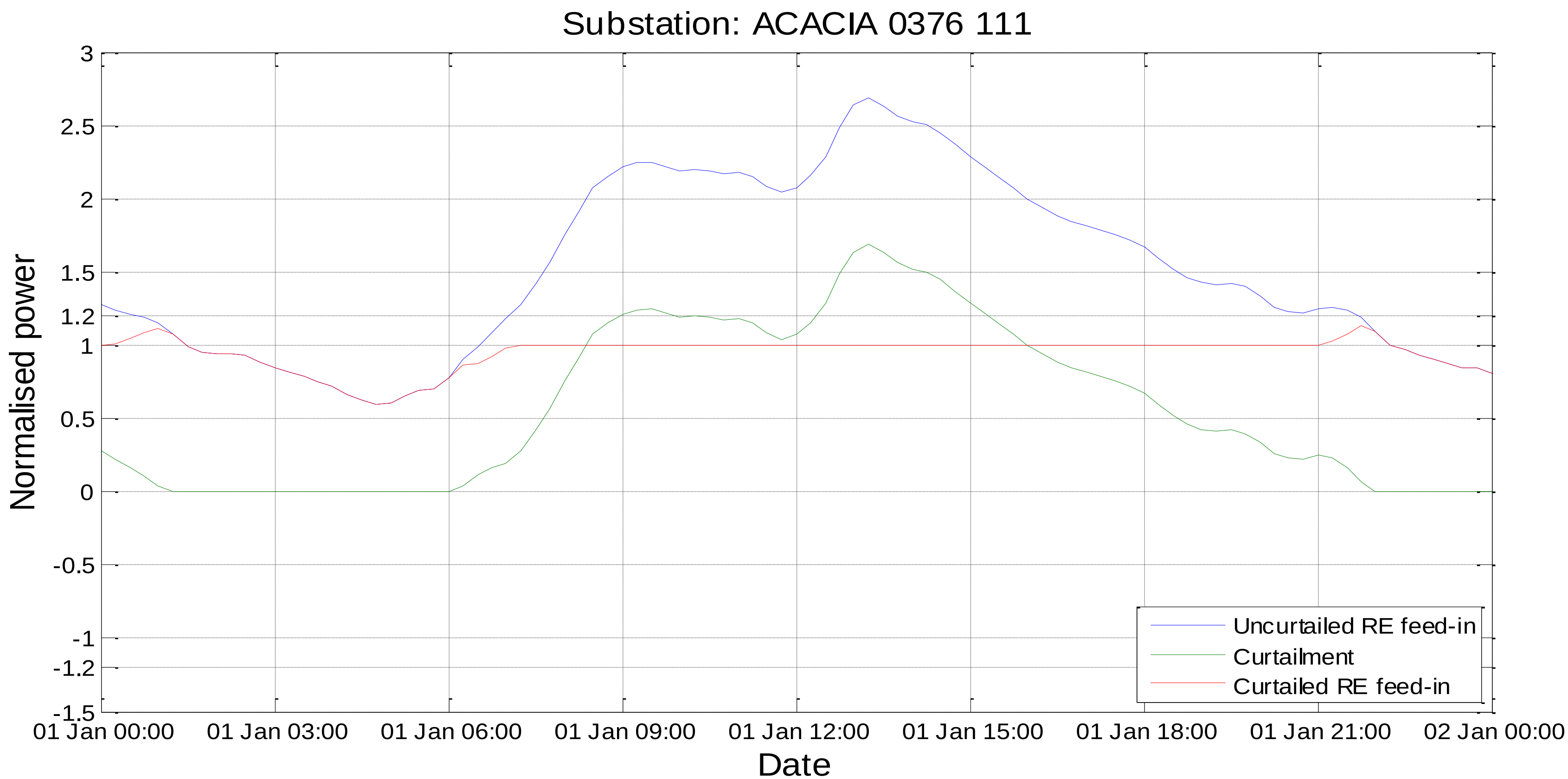
Solar PV and wind projects' power output however is generally not highly correlated

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

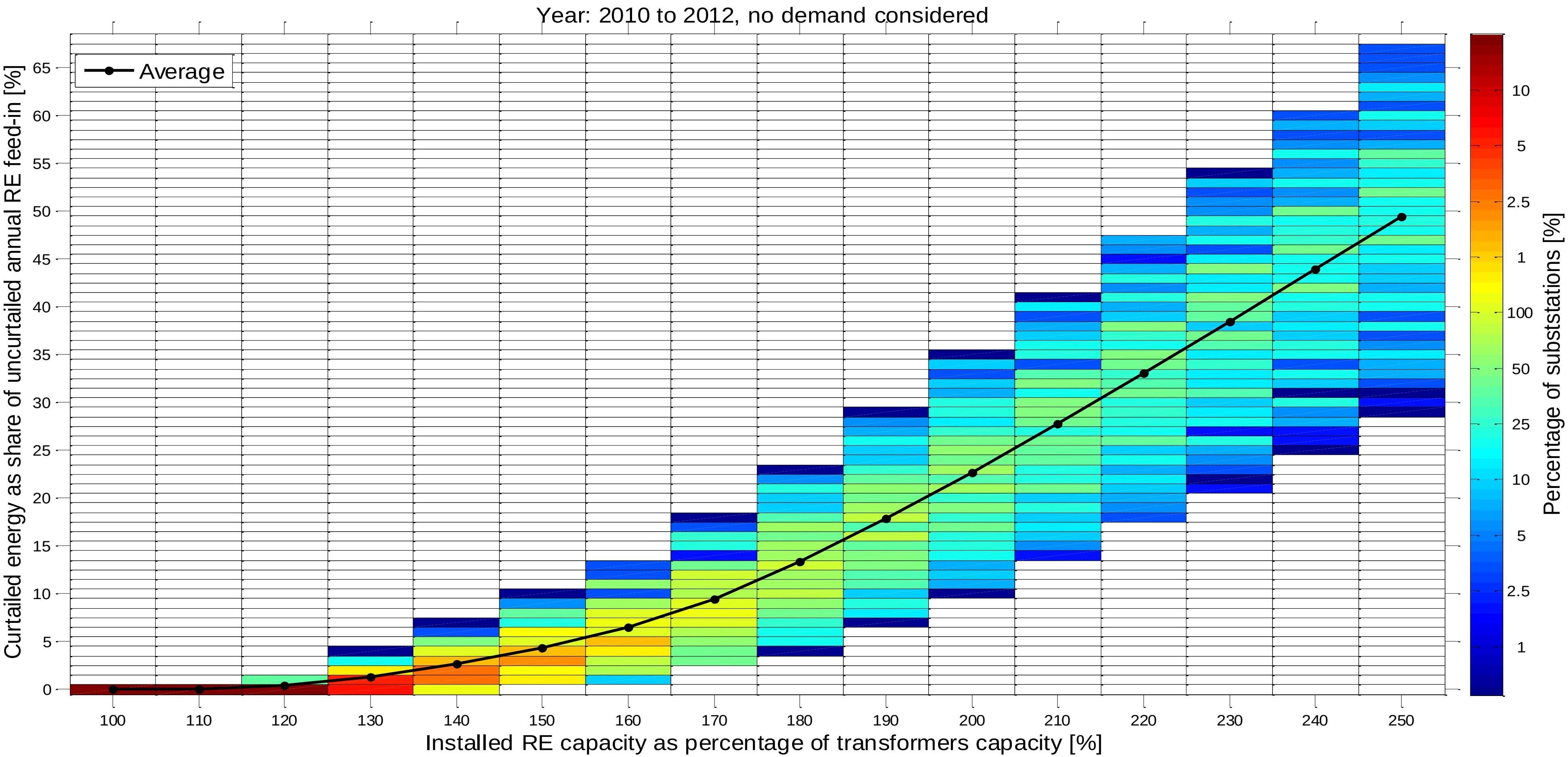
Overcapacity of wind/solar at substation leads to curtailment

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

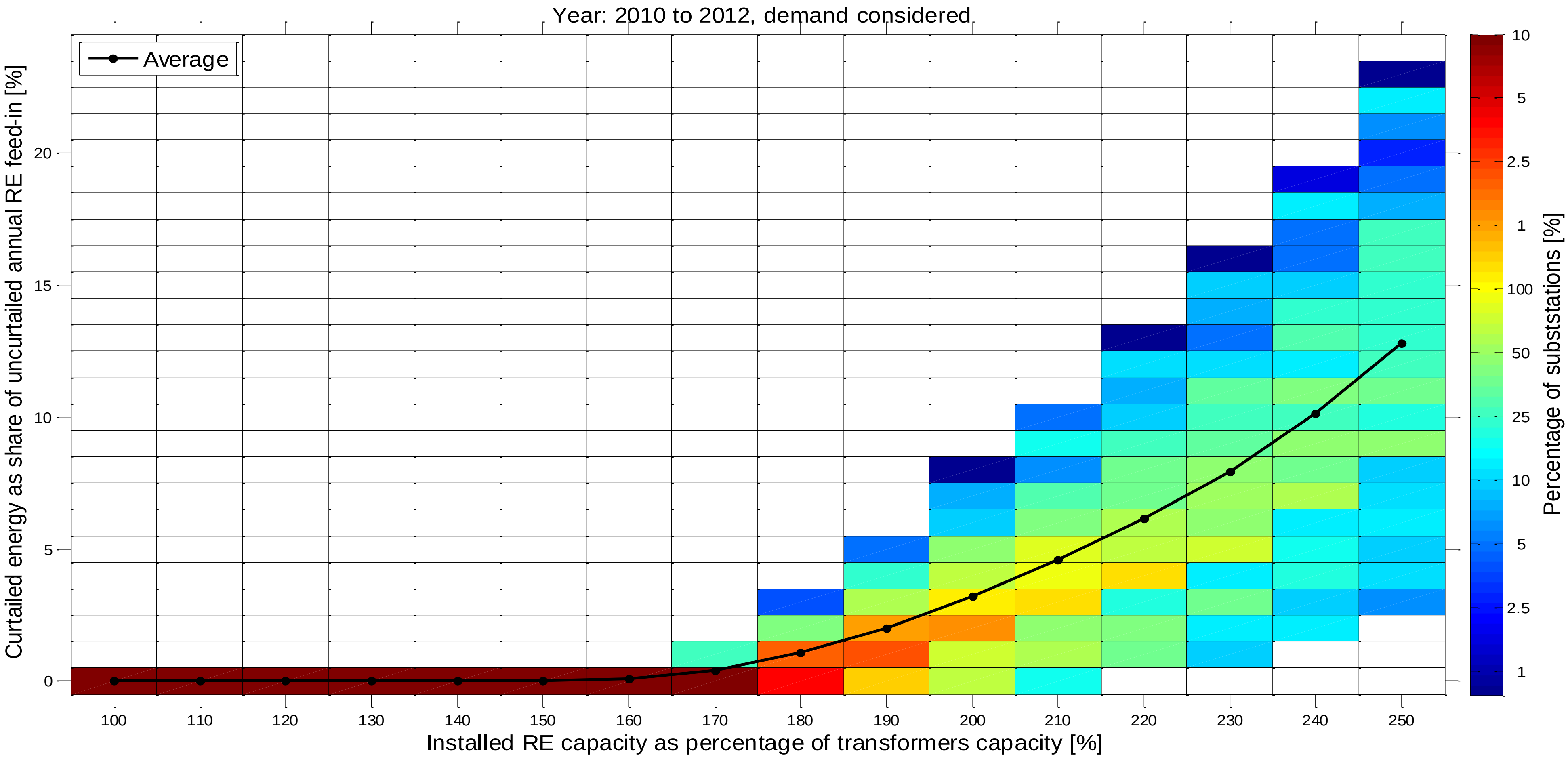
Statistical analysis of required annual curtailment across all substations (simulating only wind/PV)



REV 1

60-70% additional solar/wind can be installed per subsstation without curtailment if generic load is assumed

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



REV 1

Curtailment analysis: Results

	Curtailed annual energy per total solar/PV energy	Minimum installable solar/wind power per substation capacity	Average installable solar/wind power per substation capacity	Maximum installable solar/wind power per substation capacity
Only Feed-in	0%	120%	120%	140%
	5%	140%	130%	180%
	10%	150%	170%	200%
Feed-in and load (residual load)	0%	160%	170%	210%
	5%	190%	210%	Not evaluated yet
	10%	210%	240%	Not evaluated yet

REV 1

Contents

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 competiveness 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

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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

REV 1

Ke a leboha

ndza Khensa

Enkosi

Ngiyathokoza

Thank you

Ke a leboga

Ndi a livhuha

Dankie

Ngiyabonga

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