Solar PV resource for higher penetration through a combined spatial aggregation with wind

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Mandate of the Council for the Scientific and Industrial Research - CSIR

"The objects of the CSIR are, through **directed** and particularly **multi-disciplinary research** and **technological innovation,** to foster, in the national interest and in fields which in its opinion should receive preference**, industrial and scientific development**, either by itself or **in co-operation with principals from the private or public sectors,** and thereby to contribute to the **improvement of the quality of life** of the people of the Republic, and to perform any other functions that may be assigned to the CSIR by or under this Act."

(Scientific Research Council Act 46 of 1988,
amended by Act 71 of 1990)

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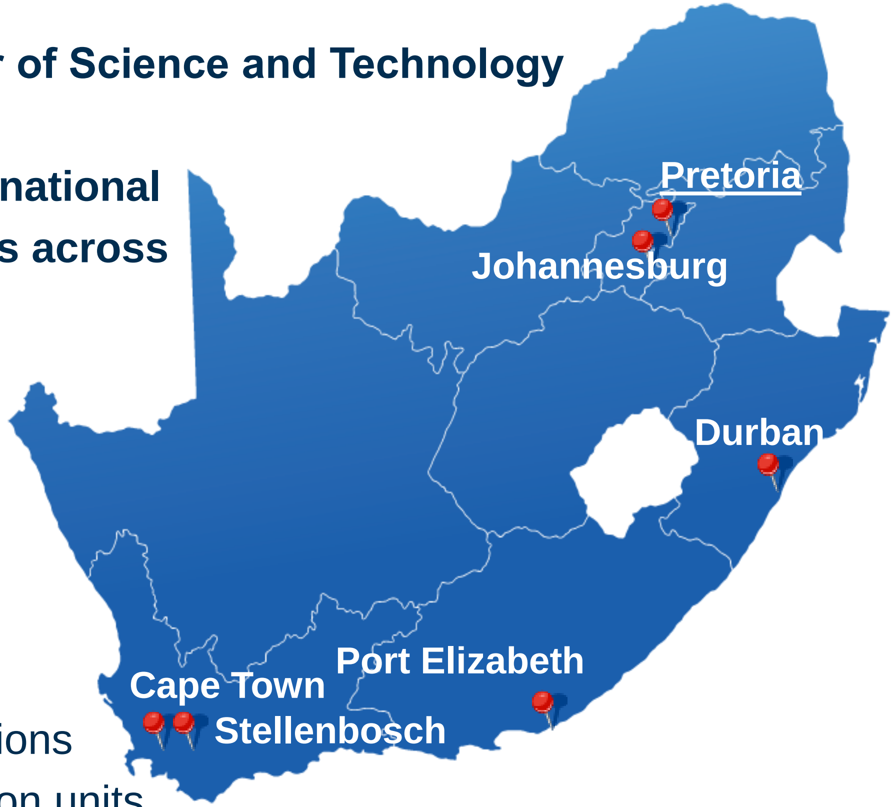
Overview of the CSIR

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
- ~ €176 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

REV 1

CSIR's new Energy Centre

"To provide the knowledge base for the South African energy transition and beyond"

Potentially 6th area: Industry Business Cases

CSIR Energy Centre research areas

Energy Efficiency & Demand Response

- Energy Efficiency in all end-use sectors
- Demand forecasting
- Demand response
- Energy statistics

Renewable Energy Technologies

- Solar
- Wind
- Biomass/-gas
- Liquid Biofuels
- Small Hydro
- Ambient Heat

Energy Storage and Hydrogen

- Energy Storage (Power-to-Power, Power-to-Heat)
- Power-to-Hydrogen
- Power-to-Gas
- Power-to-Liquids
- Electric Mobility

Energy-System Planning & Operations

- Energy Planning
- Grid Planning
- Micro and Island Grids
- System Operations
- Smarter Grids

Energy Markets and Policy

- 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

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Sources: CSIR Energy Centre analysis

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- **South African context – Solar PV and wind developments, plans and potential**

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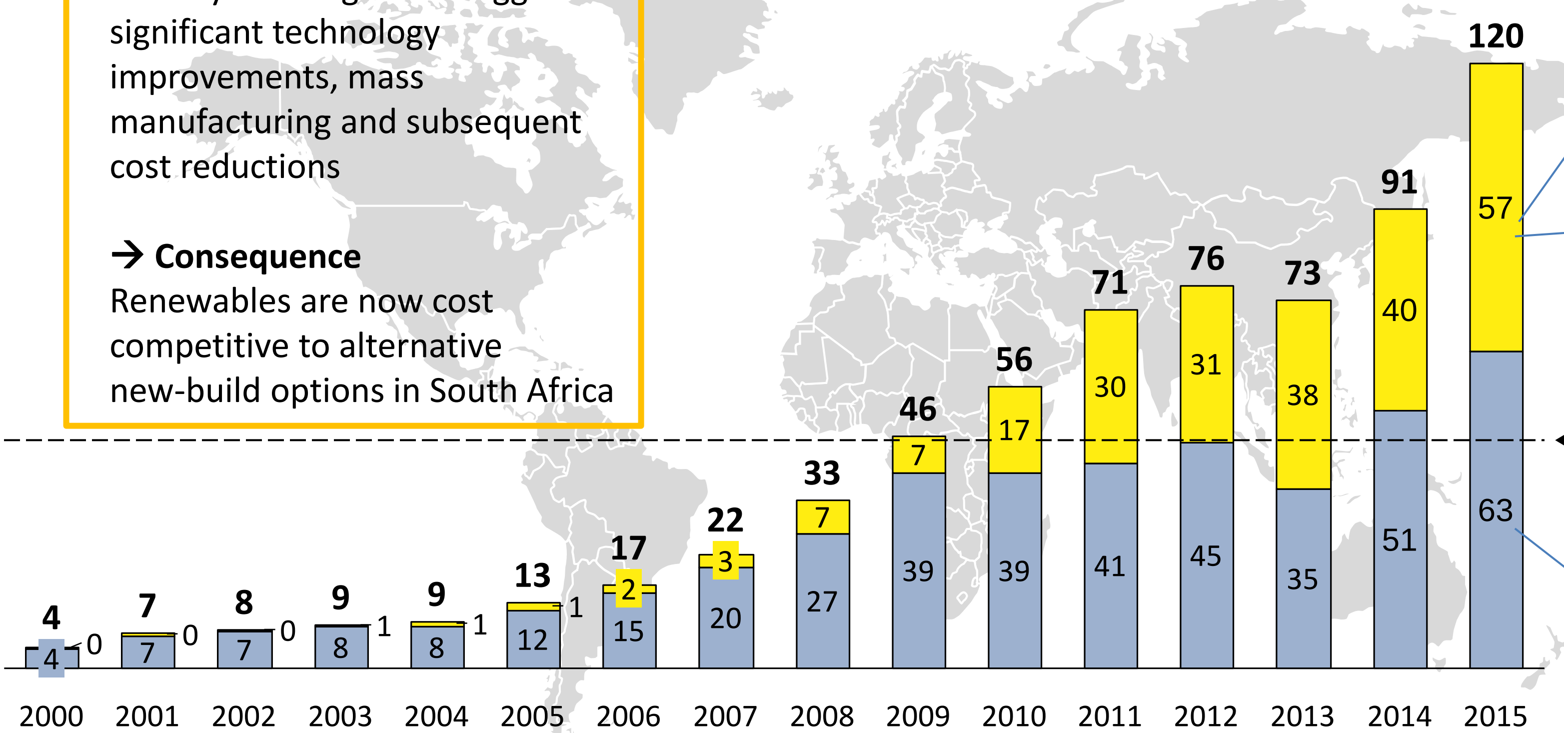
In 2015, 120 GW of wind and solar PV newly installed globally

Global annual new capacity in GW/yr

Subsidy-driven growth triggered significant technology improvements, mass manufacturing and subsequent cost reductions

→ **Consequence**
Renewables are now cost competitive to alternative new-build options in South Africa

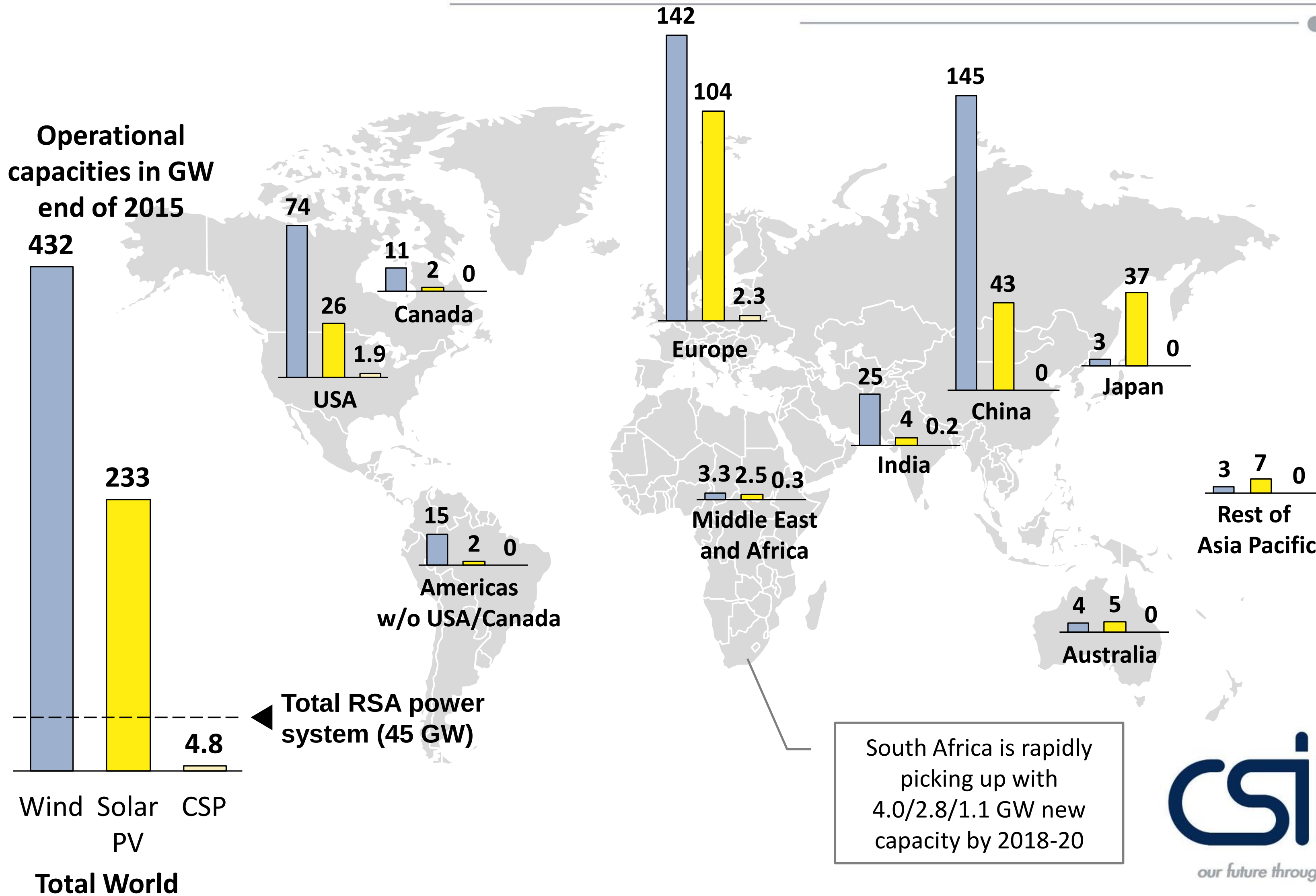


This is all very new: Almost 90% of the globally existing PV capacity was installed during the last five years alone!

Sources: GWEC; EPIA; BNEF; CSIR analysis

Renewables until today mainly driven by US, Europe, China and Japan

Globally installed capacities for three major renewables wind, solar PV and CSP end of 2015



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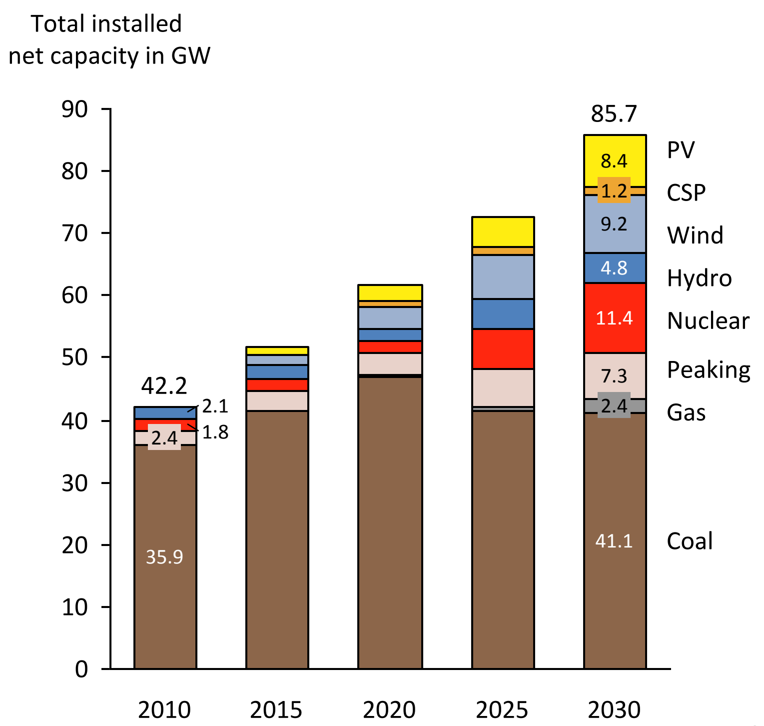
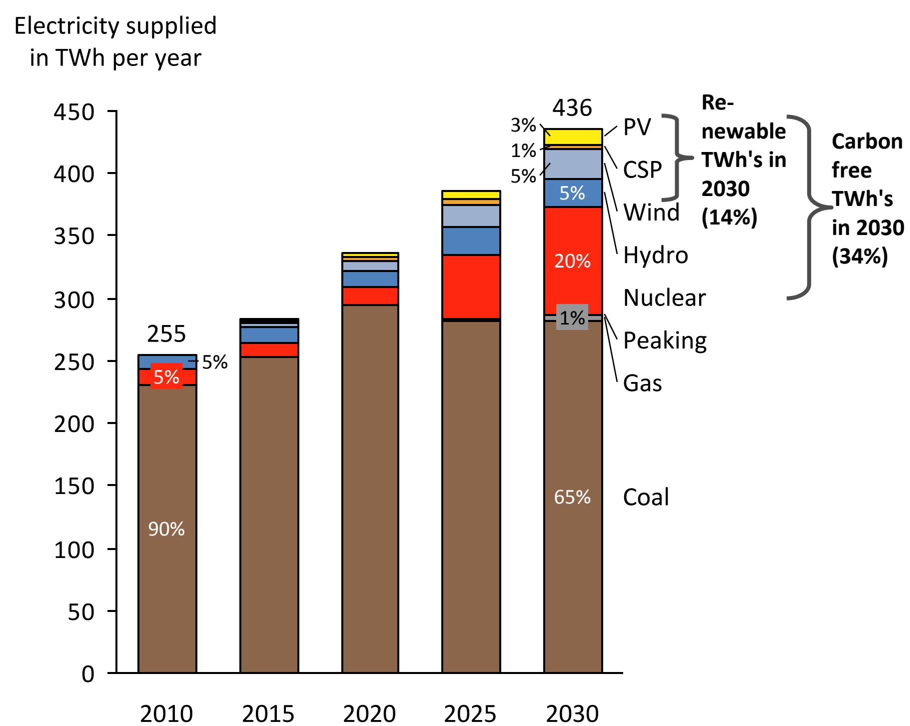
Sources: GWEC; EPIA; CSPToday; CSIR analysis

Integrated Resource Plan 2010 (IRP 2010): Plan of the power generation mix for South Africa until 2030

Installed capacity



Energy mix



Share new renewables **0%** → **9%**

Implementation of the IRP is done by Department of Energy through competitive tenders ("REIPPPP" for renewables)

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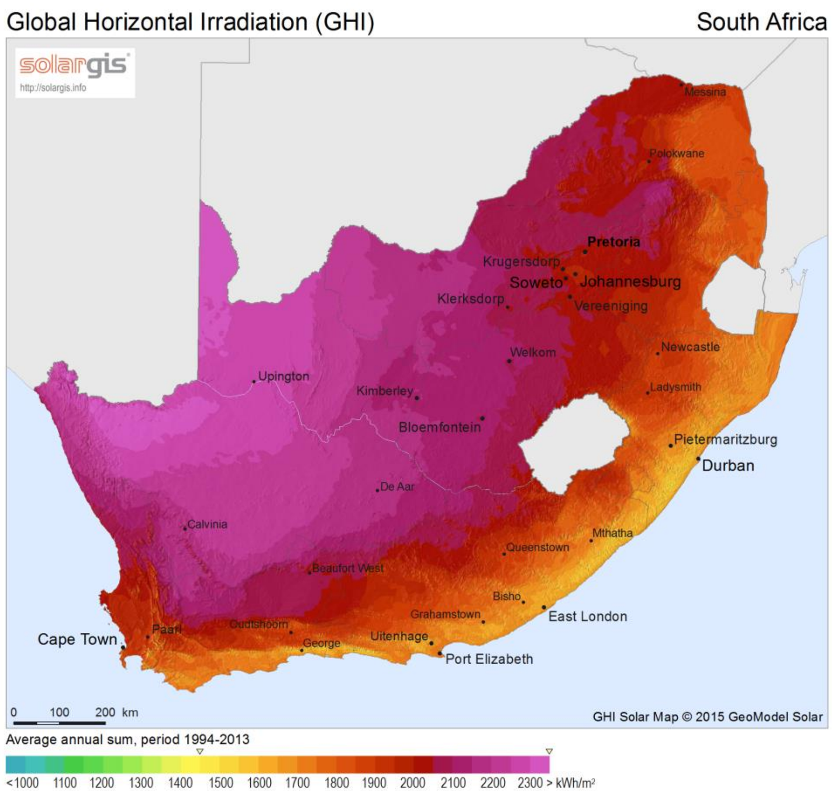
Note: hydro includes imports from Cahora Bassa

Sources: Integrated Resource Plan 2010, as promulgated in 2011; CSIR Energy Centre analysis

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

Solar resource in South Africa…



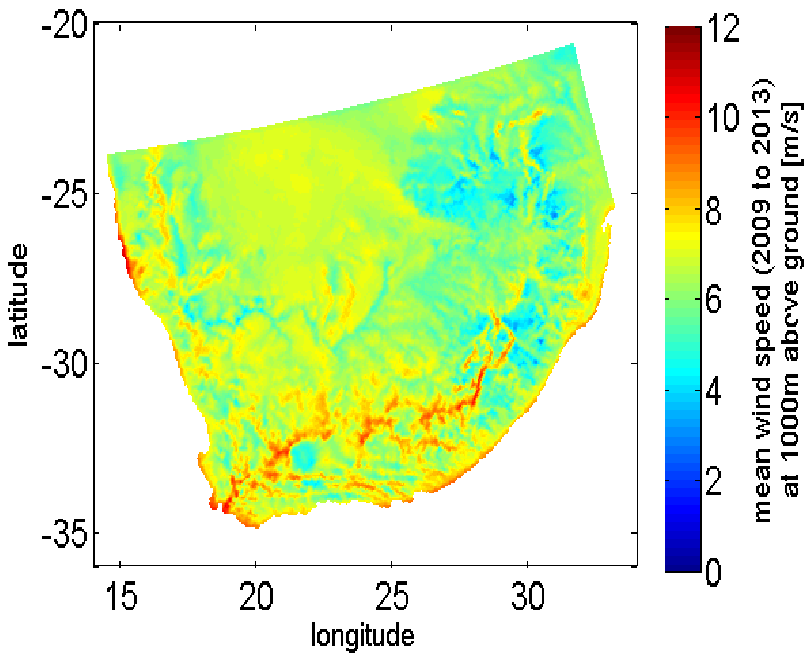
SA's planned PV capacity by 2030 of 8.4 GW – an extremely low target

… as compared to Germany

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

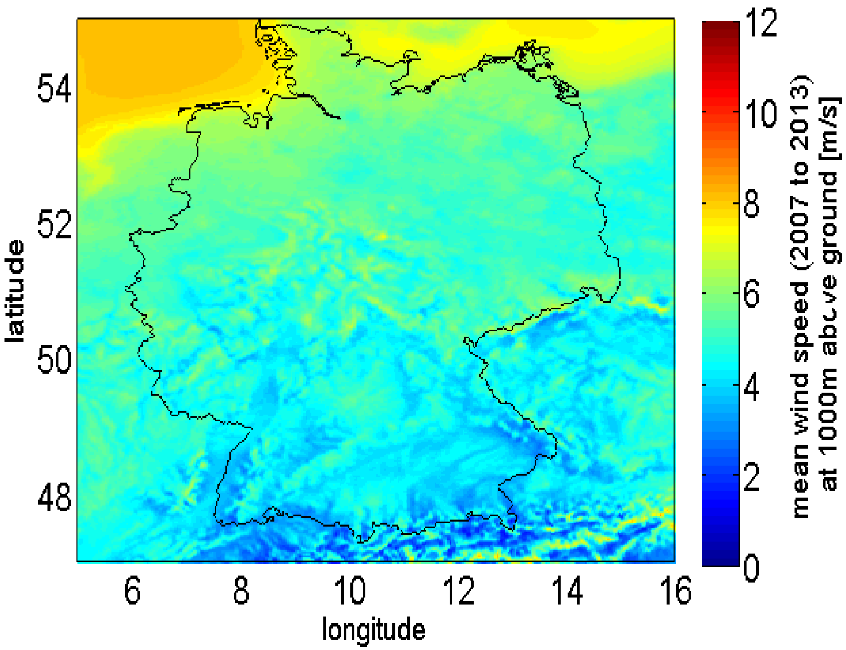
Best wind sites in Germany along the coastline have similar wind speeds as large parts of inland South Africa (yellow)

Wind resource in South Africa…



SA's planned wind capacity by 2030: 9.2 GW

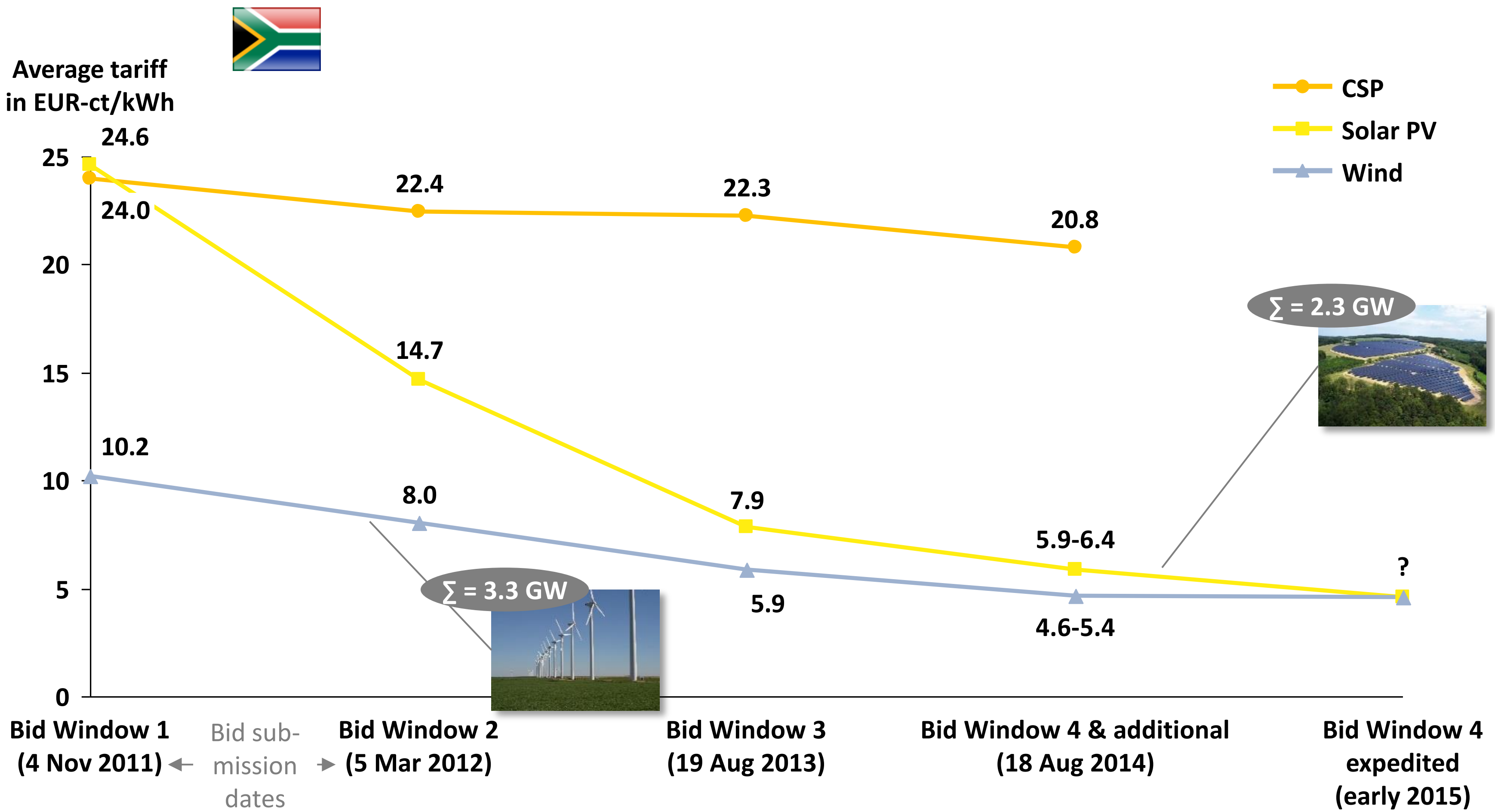
… as compared to Germany



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

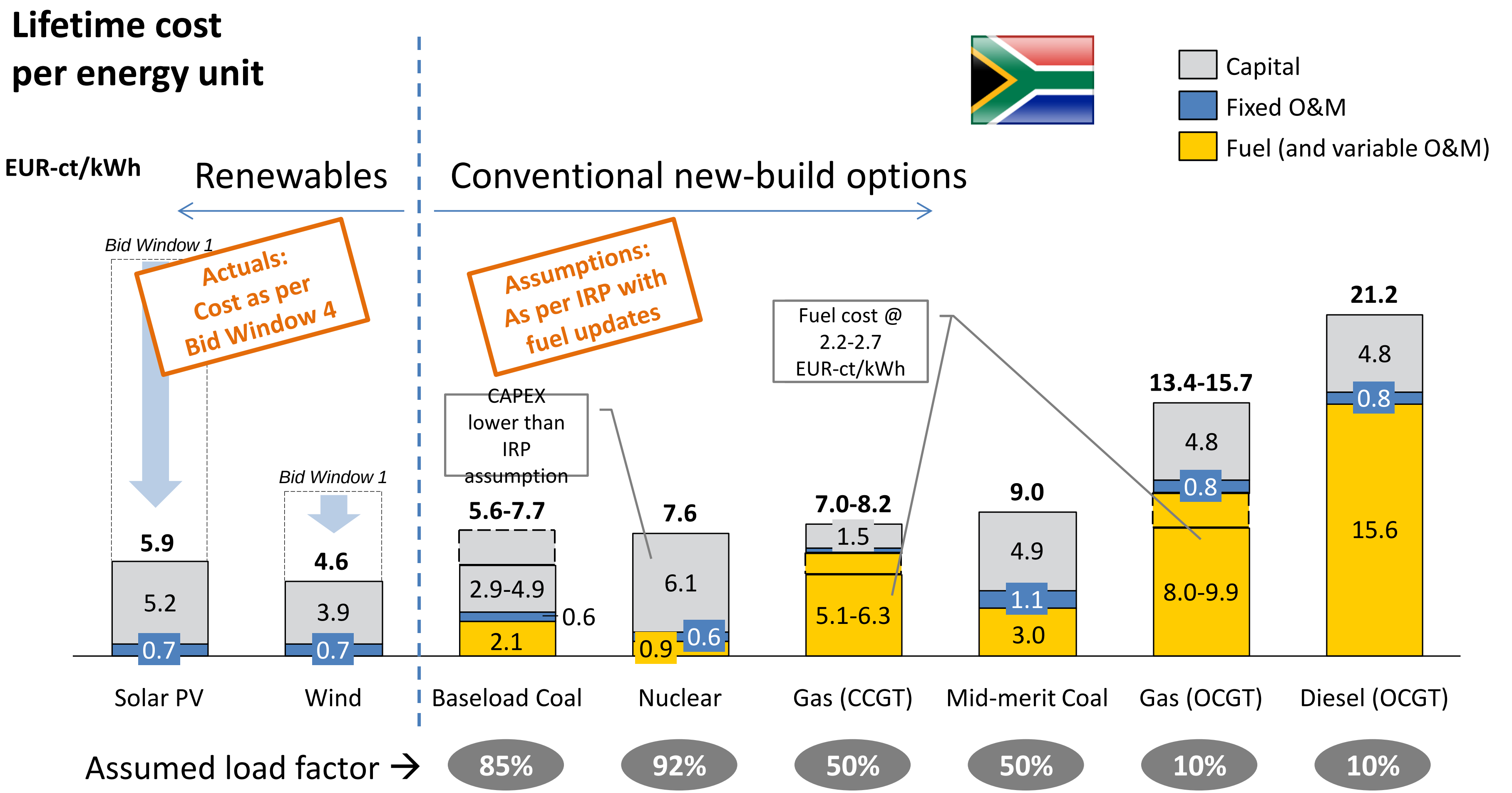
Competitive tender outcome: new wind/solar PV projects very cheap

First four bidding windows' results of Department of Energy's RE IPP Procurement Programme (REIPPPP)



Notes: For CSP Bid Window 3 and 3.5, the weighted average of base and peak tariff is indicated, assuming 50% annual load factor; BW = Bid Window; Sources: Department of Energy's publications on results of first four bidding windows http://www.energy.gov.za/IPP/List-of-IPP-Preferred-Bidders-Window-three-04Nov2013.pdf; http://www.energy.gov.za/IPP/Renewables_IPP_ProcurementProgram_WindowTwoAnnouncement_21May2012.pptx; http://www.ipprenewables.co.za/gong/widget/file/download/id/279; StatsSA on CPI; CSIR analysis

Consequence of renewables' cost reduction for South Africa: Solar PV and wind are the cheapest new-build options per kWh today

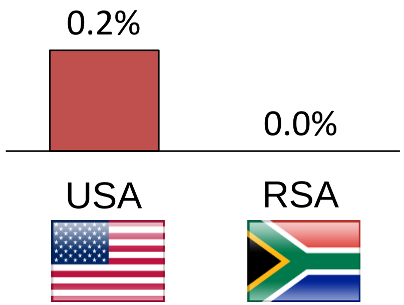


Note: Changing full-load hours for conventional new-build options drastically changes the fixed cost components per kWh (lower full-load hours → higher capital costs and fixed O&M costs per kWh); Assumptions: Average efficiency for CCGT = 55%, OCGT = 35%; nuclear = 33%; IRP costs from Jan-2012 escalated to Jul-2015 with CPI; assumed EPC CAPEX inflated by 10% to convert EPC/LCOE into tariff; Sources: IRP 2013 Update; DoE REIPPPP; StatsSA for CPI; Eskom financial reports for coal/diesel fuel cost; CSIR analysis

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

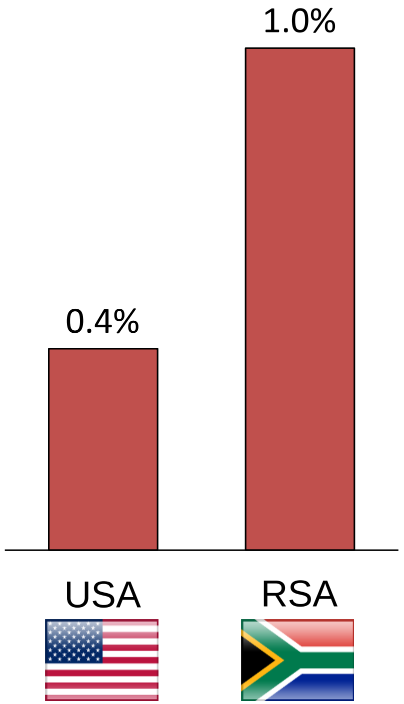
2013

Share of solar PV in electricity production



2015

Share of solar PV in electricity production



Sources: EIA; CSIR

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Solar and wind aggregation study: Main objective to quantify the effects of spatial distribution PV + wind output

Increase the fact base and understanding of aggregated PV and wind power profiles for different spatial distributions in South Africa

Resulting in:

- Confidence in integrating higher renewables shares
- Optimal mix of PV and wind, to minimise cost and ensure grid stability

Transfer of knowledge and skills on utilising wind data in energy-planning activities

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

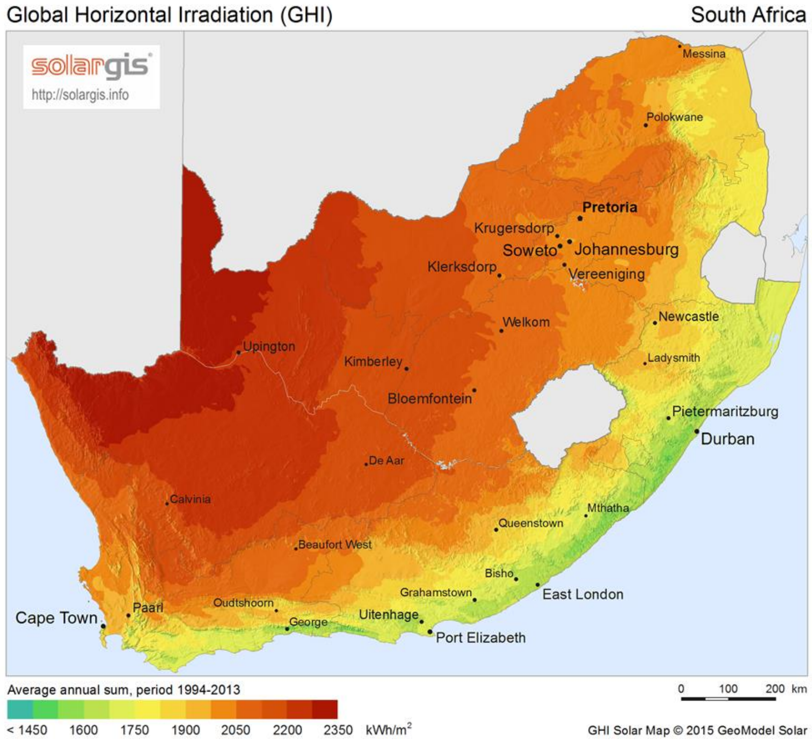
Solar Radiation Data (SoDa) was used to simulate solar PV power across South Africa

Output: Simulated time-synchronous solar PV and wind power production time-series

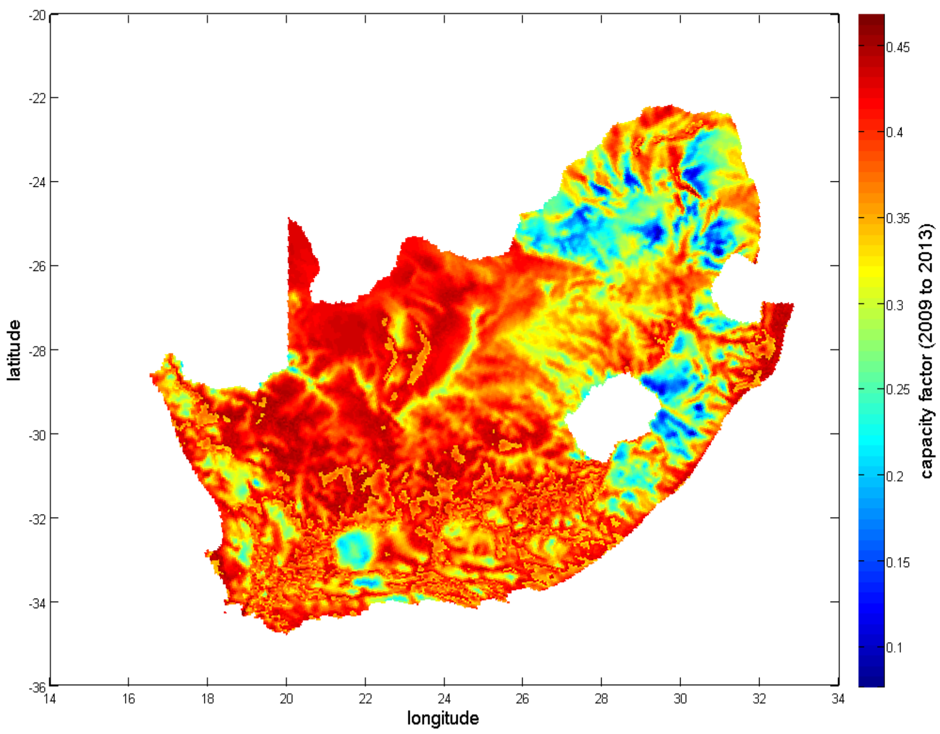
- 5 km x 5 km spatial resolution
- Almost 50,000 pixels covering entire South Africa
- 15-minute temporal resolution
- 5 years temporal coverage (2009-2013)

Solar PV and wind resource in South Africa are on par – a good motivation for combined spatial aggregation

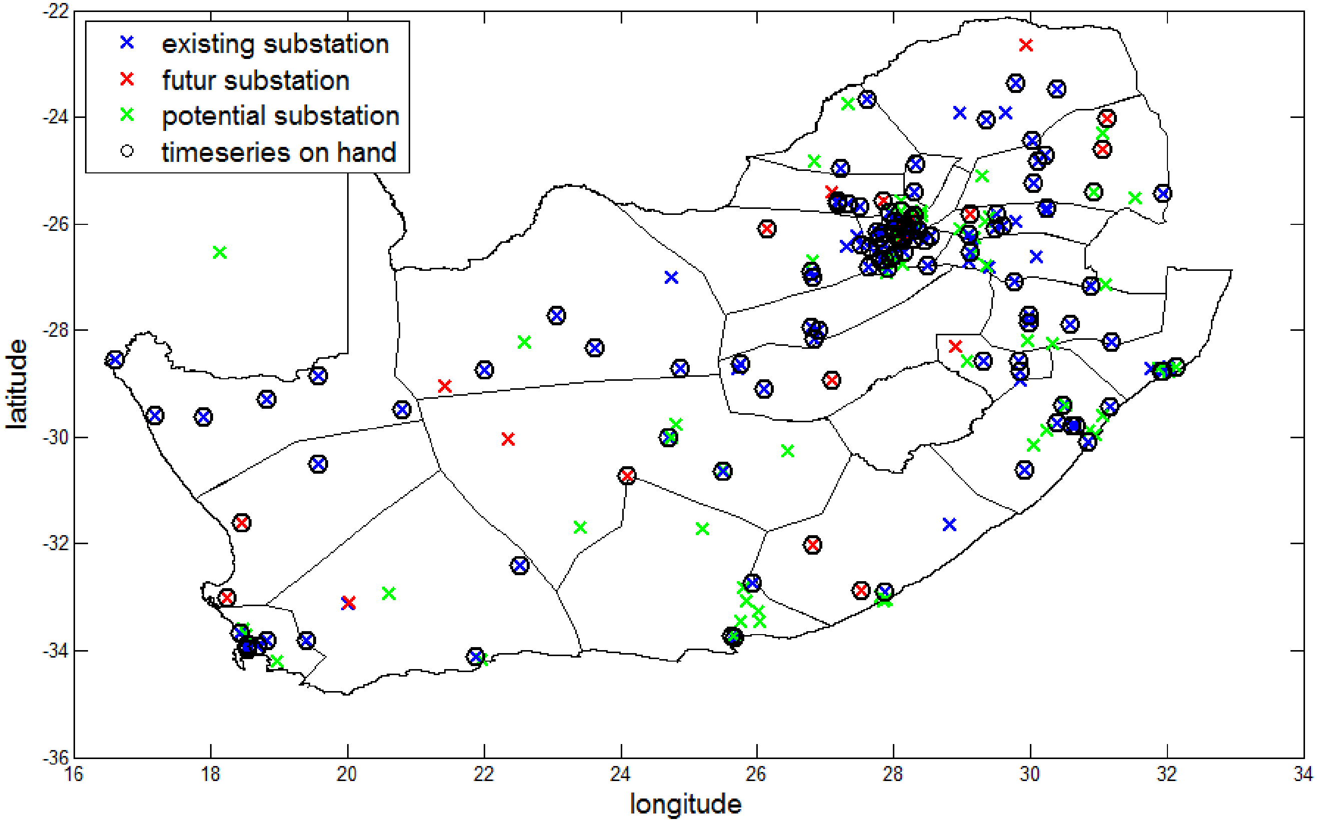
Solar PV map: ***1900 kWh/m2 achievable for ≈ 80% of the land***



Wind load factor map: ***over 30% load factor (types 1,2 & 3 turbines) for ≈ 80% of the land***



Transmission grid (current and future) is widespread thus ideal to facilitate PV and wind spatial distribution



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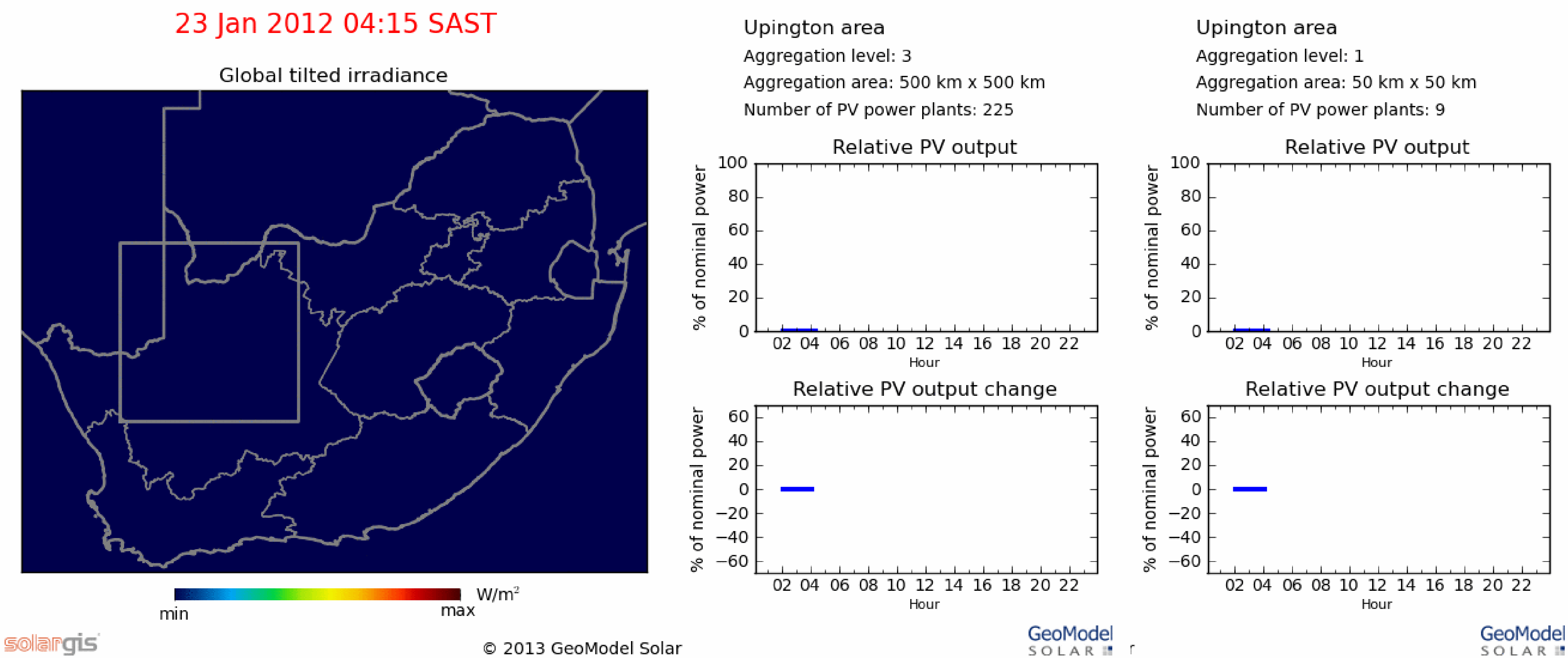
Previous solar PV study: Aggregating 225 PV plants over 500 x 500 km reduces short-term fluctuations to almost zero

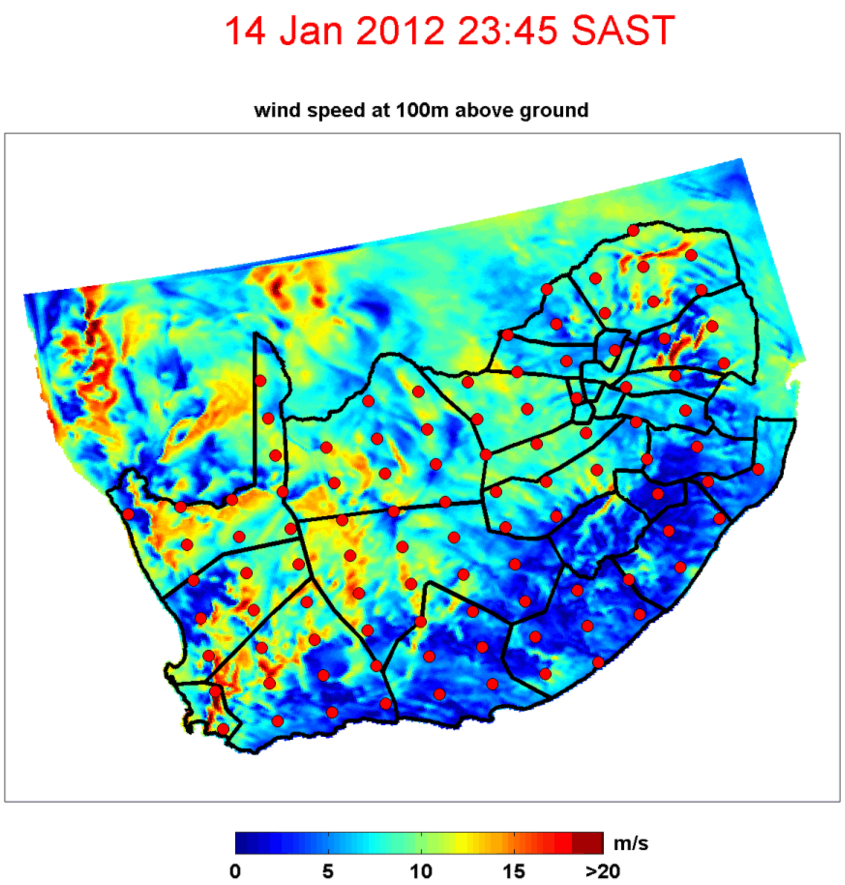


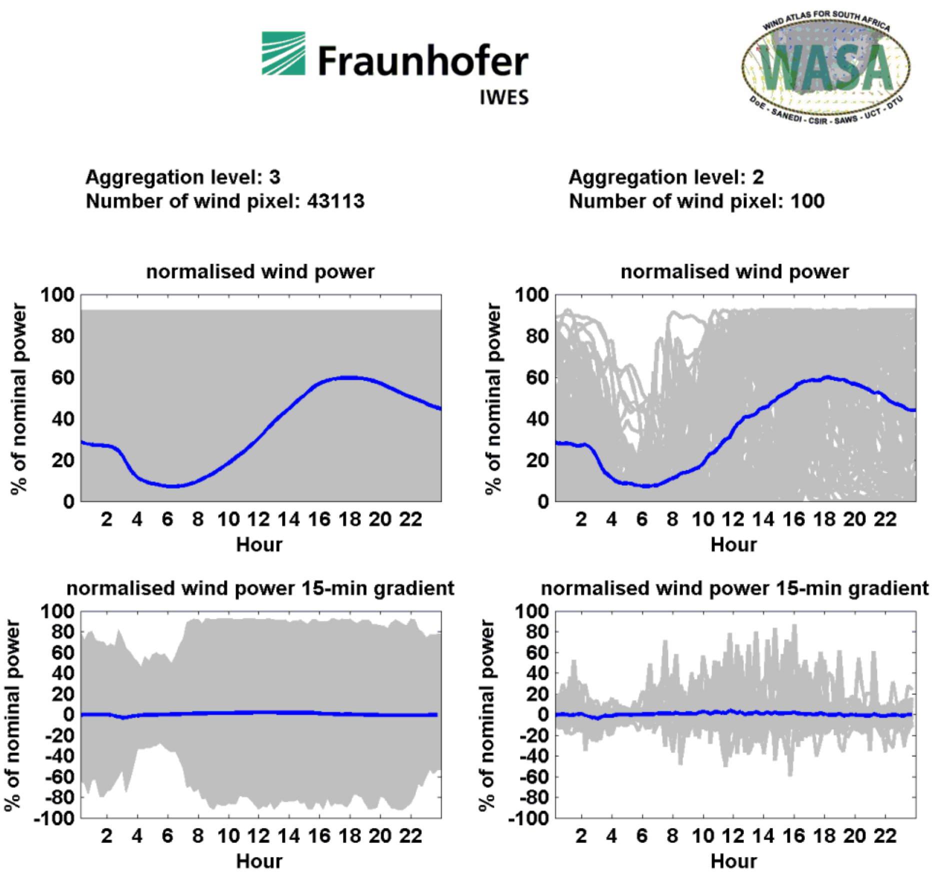
Widespread spatial distribution makes aggregated PV power output very predictable and smooth

Source: Cloud Cover study commissioned by Eskom

Aggregation across entire country: wind output very smooth

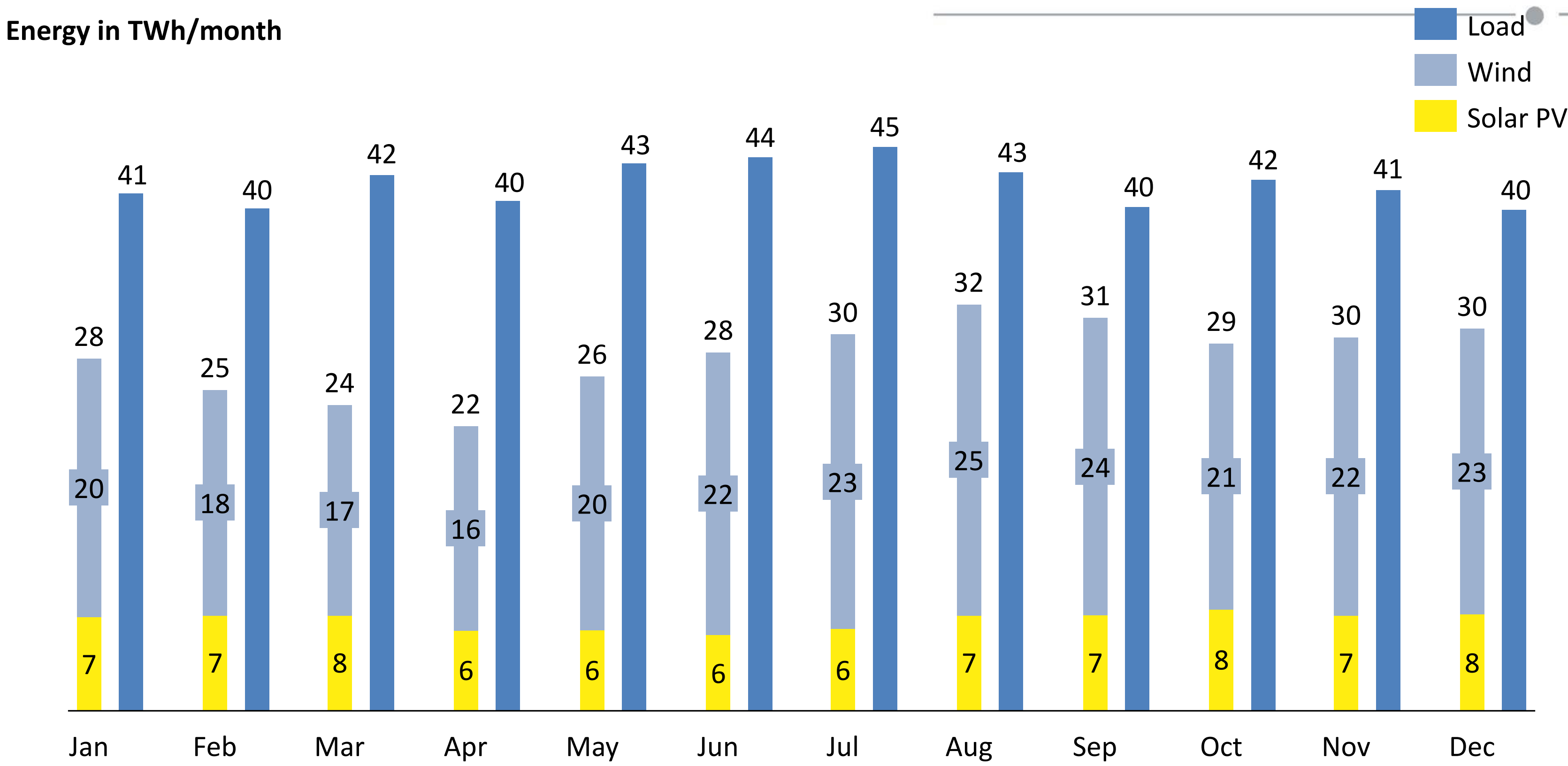
Simulated wind-speed profile and wind power output for 14 January 2012





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

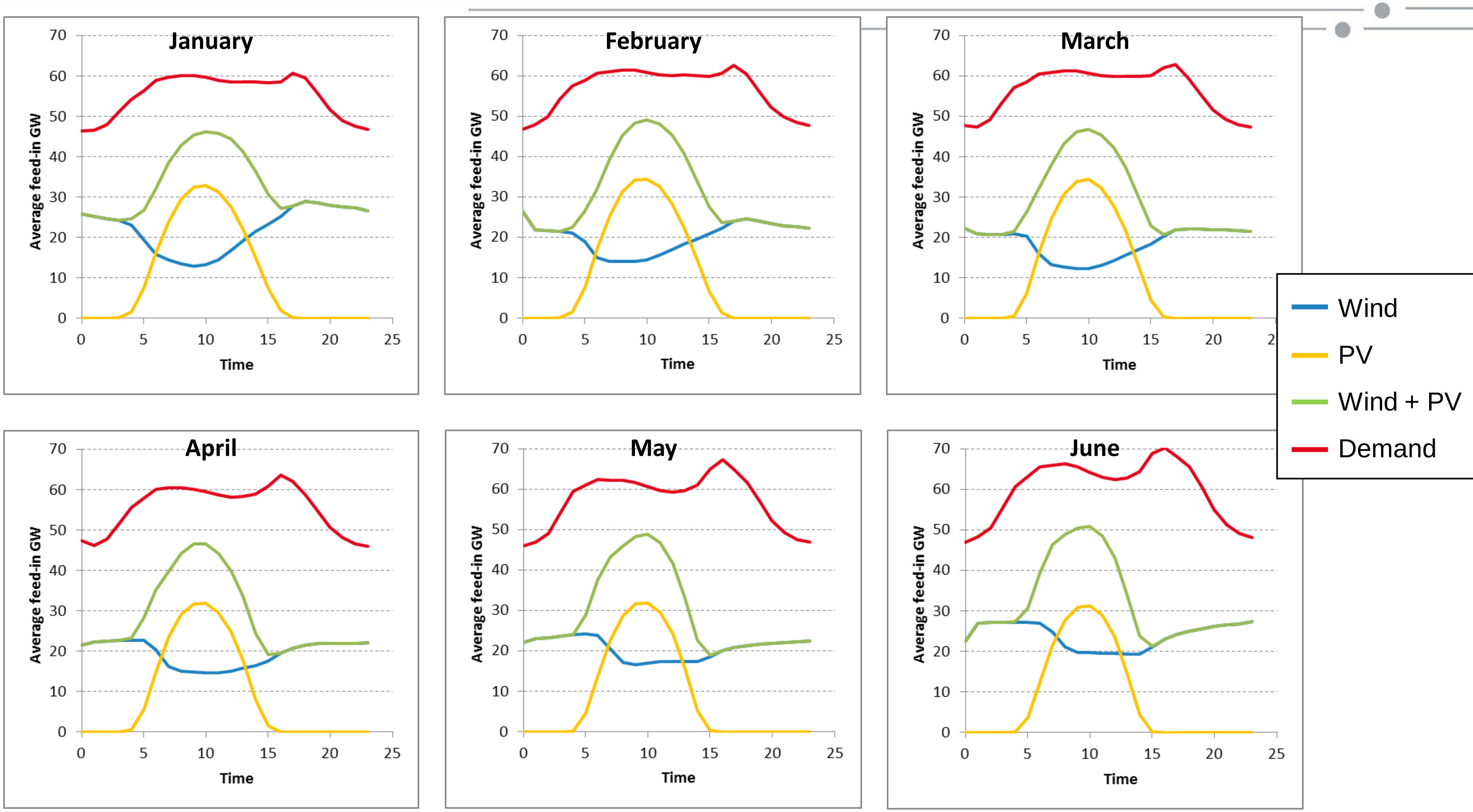


→ PV: nearly no seasonality

→ 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



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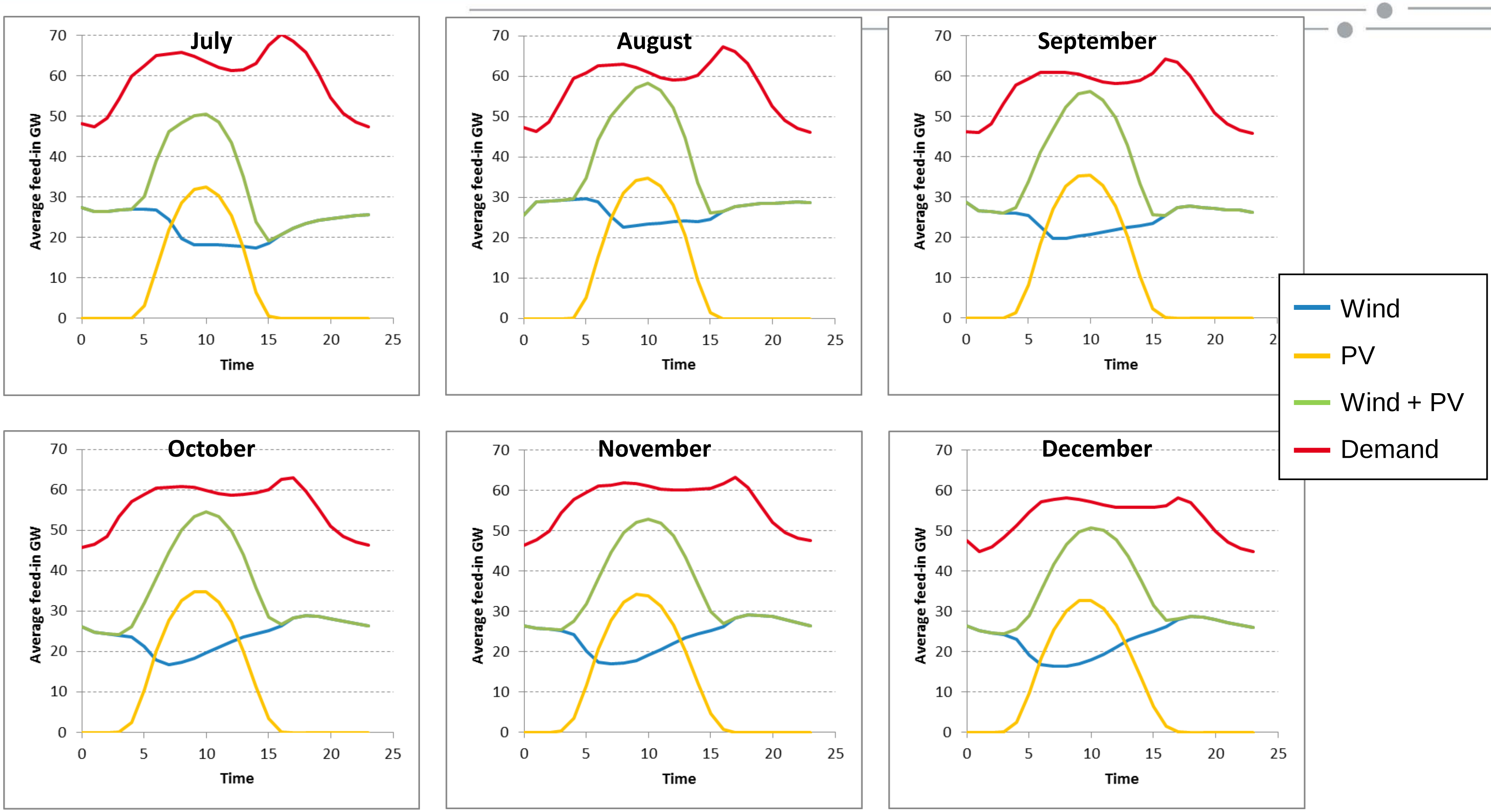
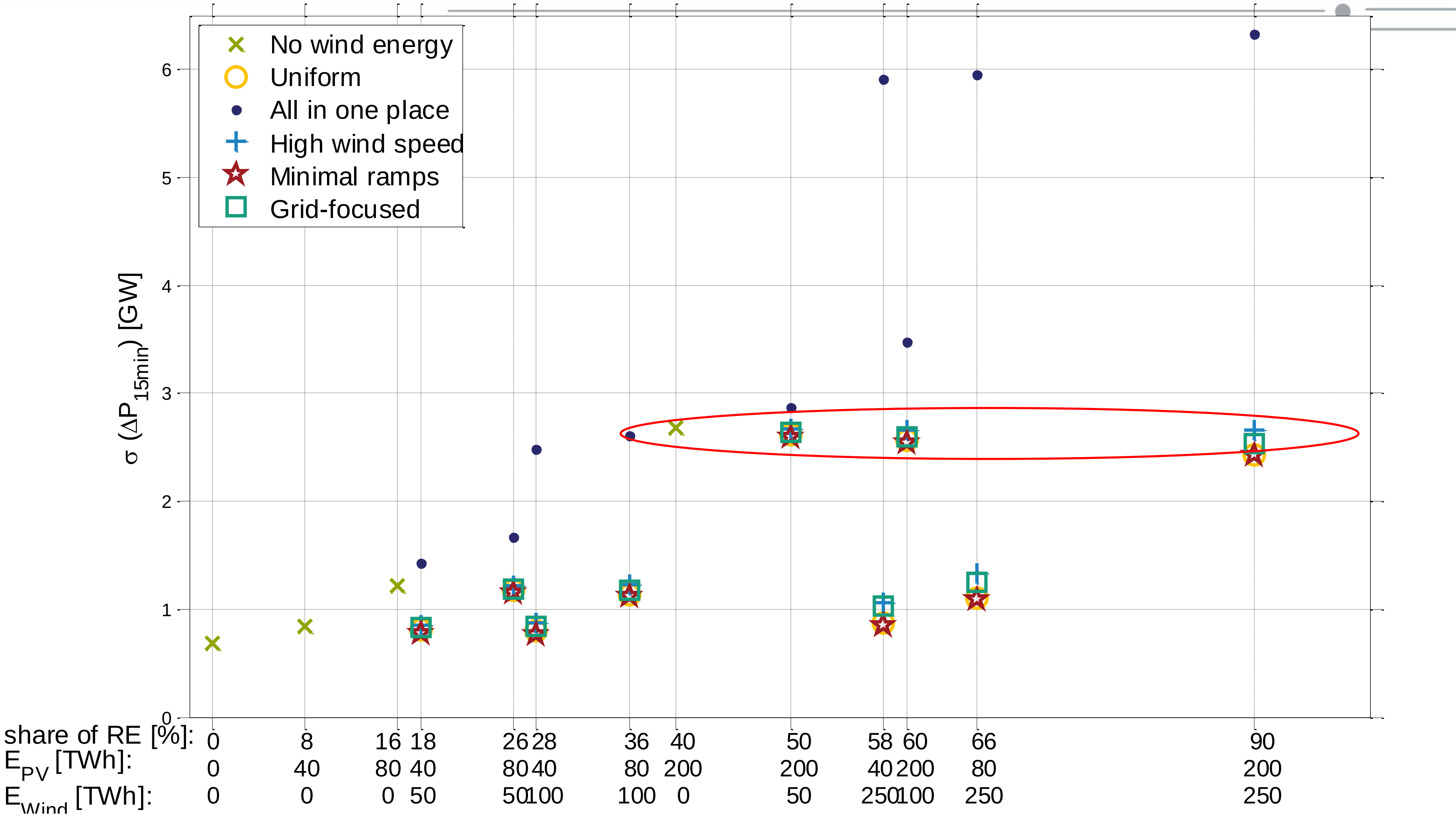


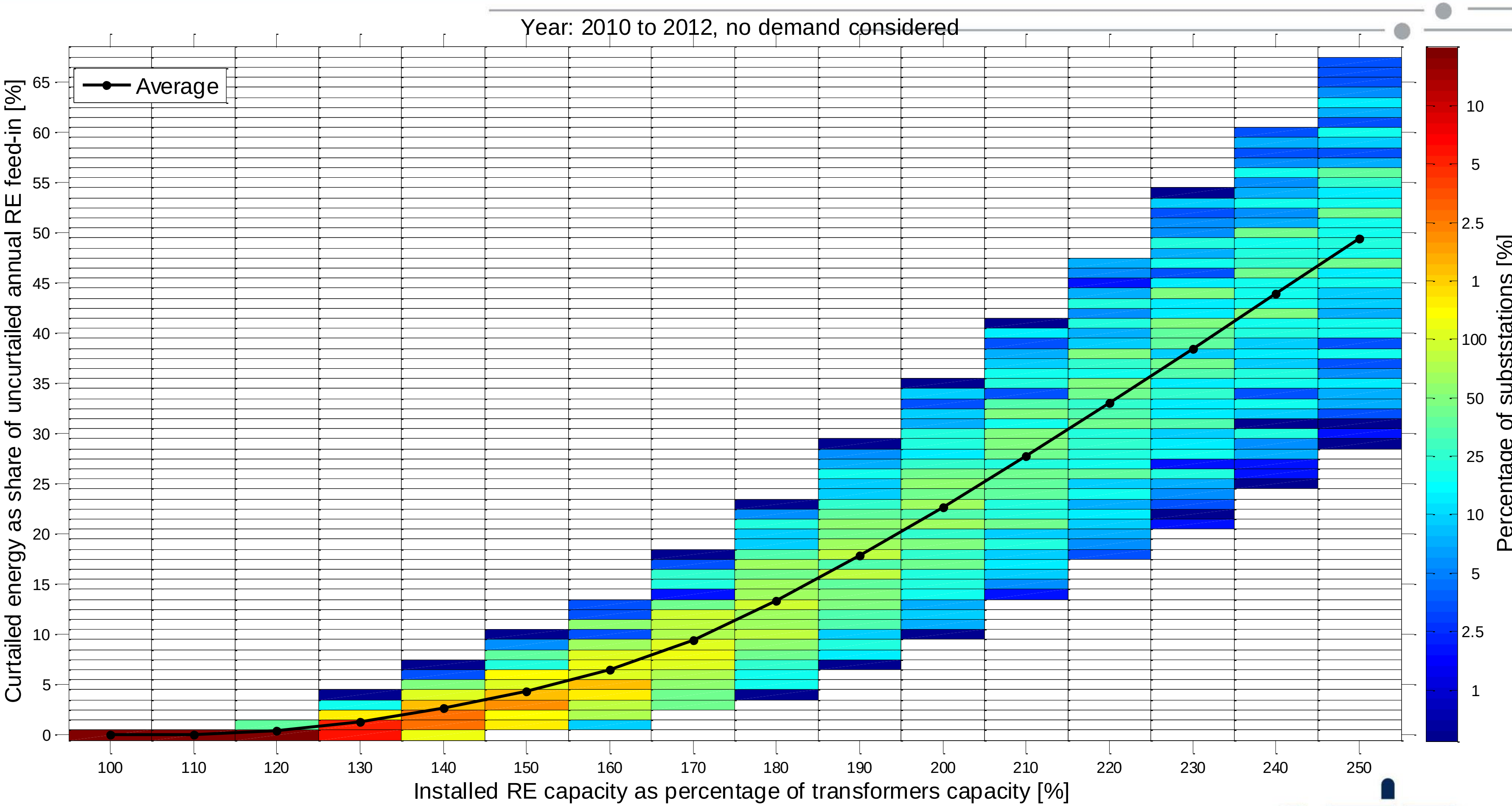
15-min gradients do not increase with higher wind penetration

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



20% additional solar/wind can be installed without curtailment

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



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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

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

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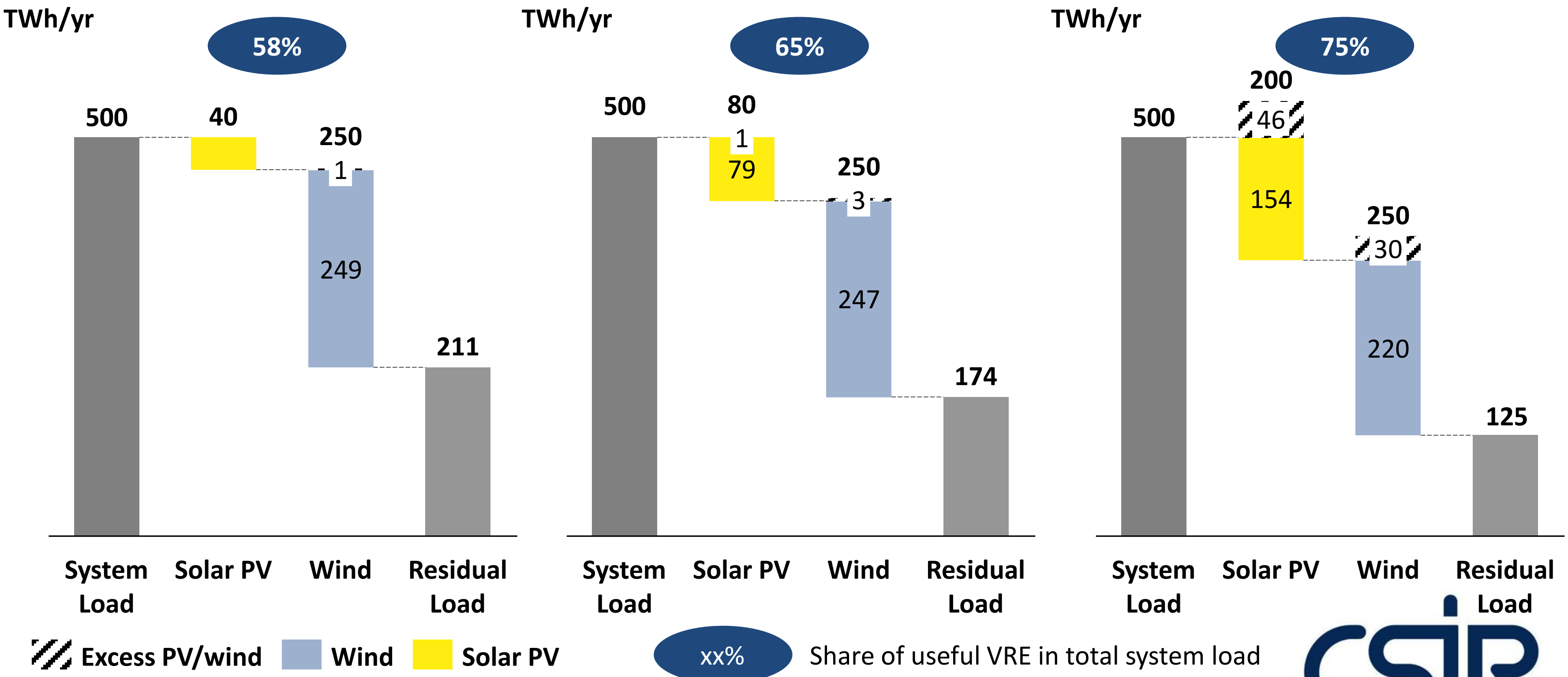
65% VRE share achievable with almost no excess energy

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



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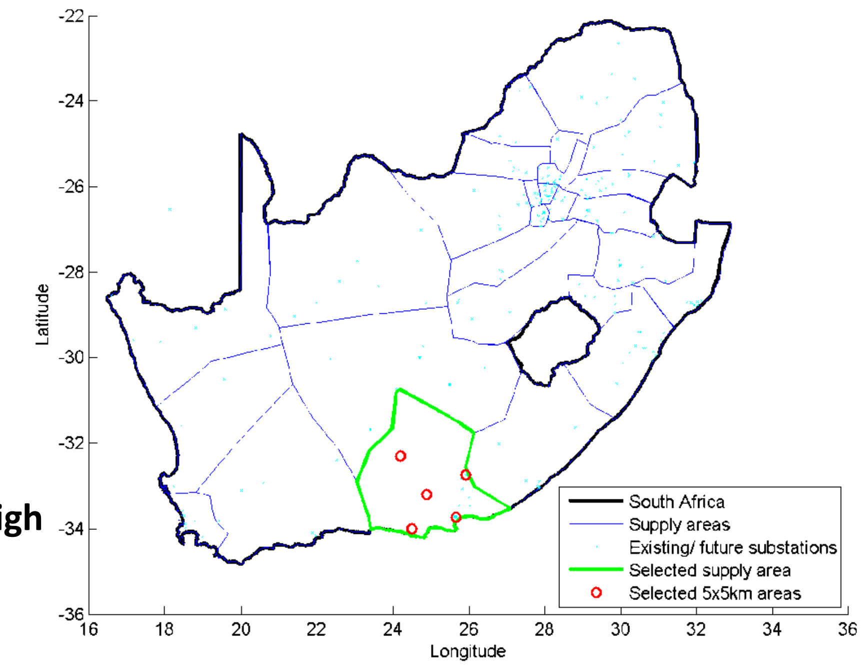
Case study:
Supply areas of South Africa

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**



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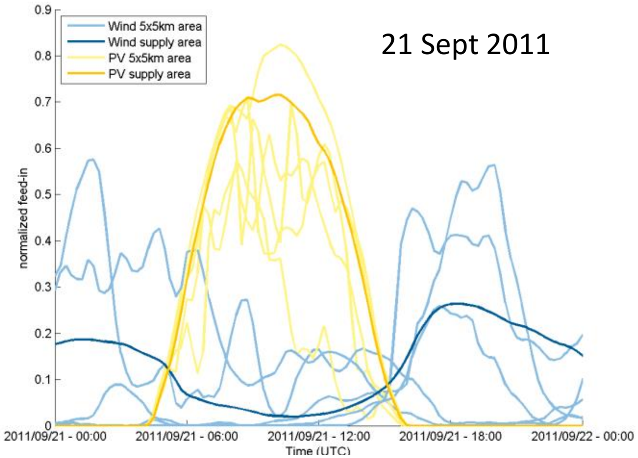
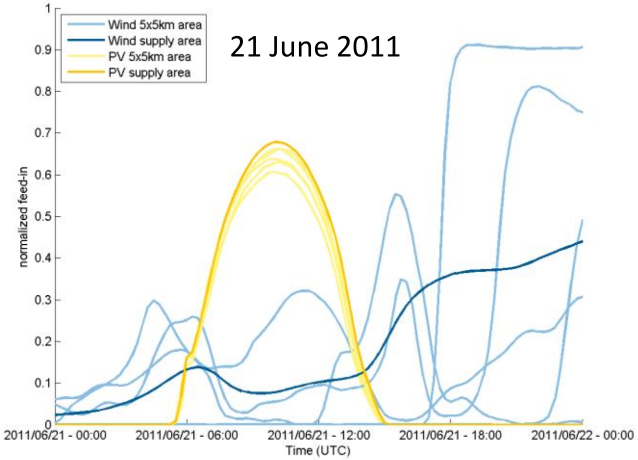
First results show on two specific days how volatility of wind and solar reduces with spatial aggregation





- Individual plants have high ramp rates
- Individual plant power output very volatile; low predictability

- Area (aggregated) output is much smoother with low ramp rates
- Aggregated plant output is more predictable

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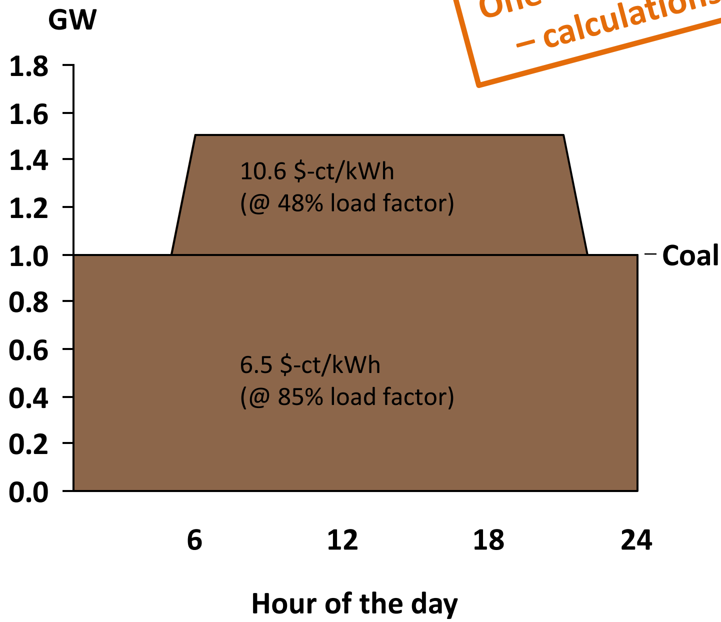
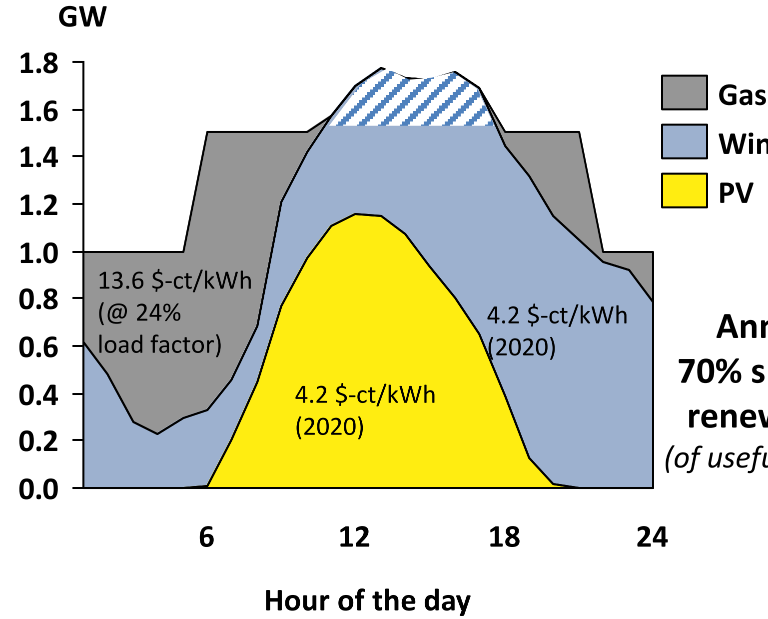
By 2020, a mix of PV, wind and flexible gas (LNG-based) costs the same as new coal, even without any value given to excess wind/PV energy

One illustrative winter day in display – calculations done for a full year





Annual: 70% share of renewables *(of useful energy)*

Technology: Coal base / coal mid-merit
Size: 1.18 / 0.56 GW
Energy: 11.1 TWh/yr

Weighted cost: **7.3 $-ct/kWh**

CO2: ~0.95 kg/kWh

Technology: PV / wind / gas
Size: 1.5 / 2.0 / 1.61 GW
Energy (useful): 11.1 TWh/yr
Energy (total): 3.6 / 5.3 / 3.2 TWh/yr = 12.1 TWh/yr

Weighted cost: **7.3 $-ct/kWh**
(per useful energy, i.e. no value given to excess)

CO2: ~0.18 kg/kWh (per useful energy)

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A future power system supplied by solar PV and wind, in combination with a flexible plant, is possible in South Africa

- Solar PV and wind energy are very low-cost bulk energy providers in South Africa; resource potential far exceeds the current and future electricity demand
- Solar PV and wind supply complement each other; PV high during mid-day and wind is higher in the evening to night time.

- Cost not a barrier anymore: new wind now costs 0.6 R/kWh (< 5 €ct/kWh) and new solar PV costs 0.8 R/kWh (< 6 €ct/kWh), based on actual PPA tariffs
- Short term fluctuations in the aggregated solar PV and wind power feed-in are significantly reduced by wide spatial distribution. Although PV is main cause of 15-min gradient changes, it is highly predictable.
- A widespread interconnected grid enables spatial aggregation

- Up to 65% energy share of variable renewable energy (VRE) are achievable with no excess energy.
- 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 PV and wind in the system
- Low seasonality of Solar PV and wind makes integration easier (no seasonal storage required)
- Distributing solar PV and wind plants widely leads to a forecast error improvement for intra-day and for day-ahead compared to putting all Solar PV plants and wind turbines in one place

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