High-renewables scenarios

Thought experiments for the South African power system

CSIR Energy Centre

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CSIR's new Energy Centre streamlines and expands CSIR's energy research offerings in five areas – today: 25 employees, growing

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 & Operat.

- 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

Energy-Autonomous Campus (EAC) Programme

Five year objective: approx. 120-150 staff to be able to address all relevant dimensions of RSA's energy transition

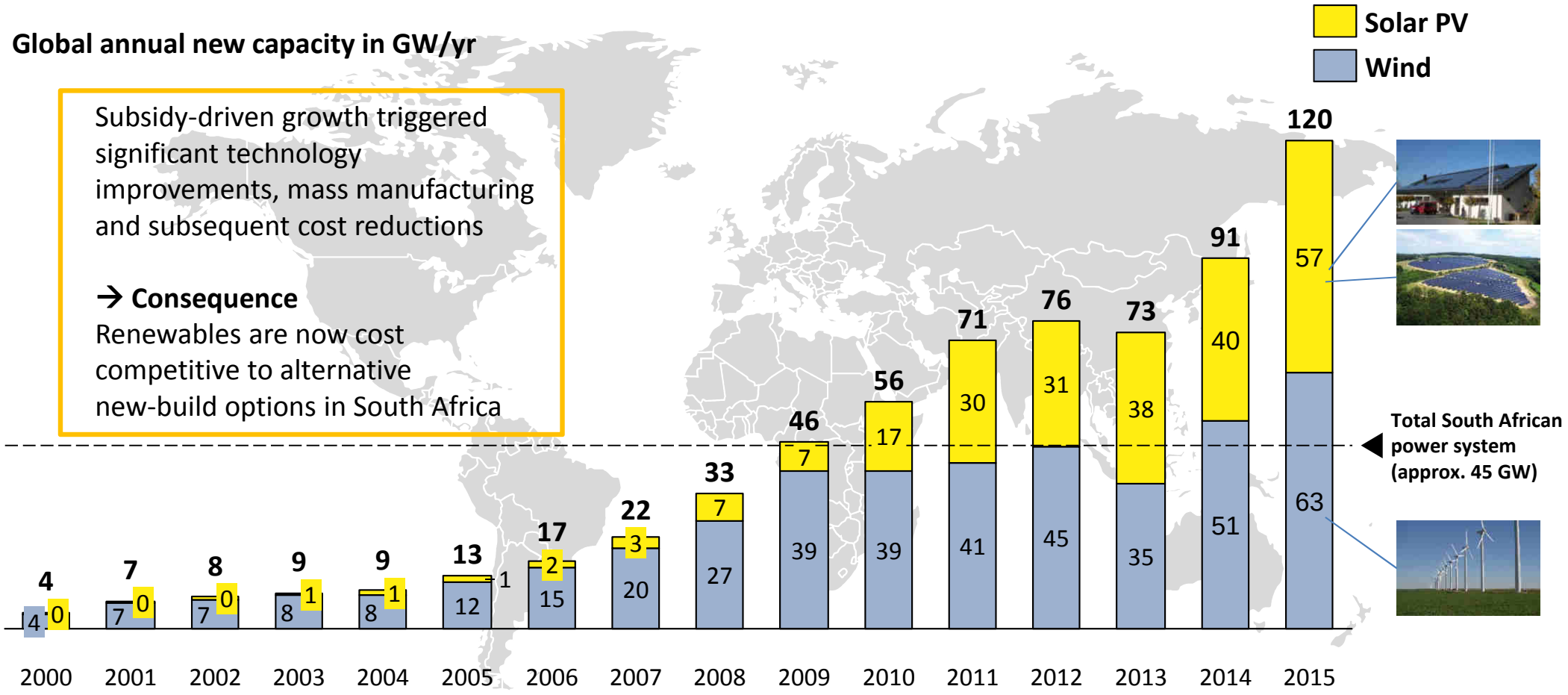
Sources: CSIR Energy Centre analysis

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

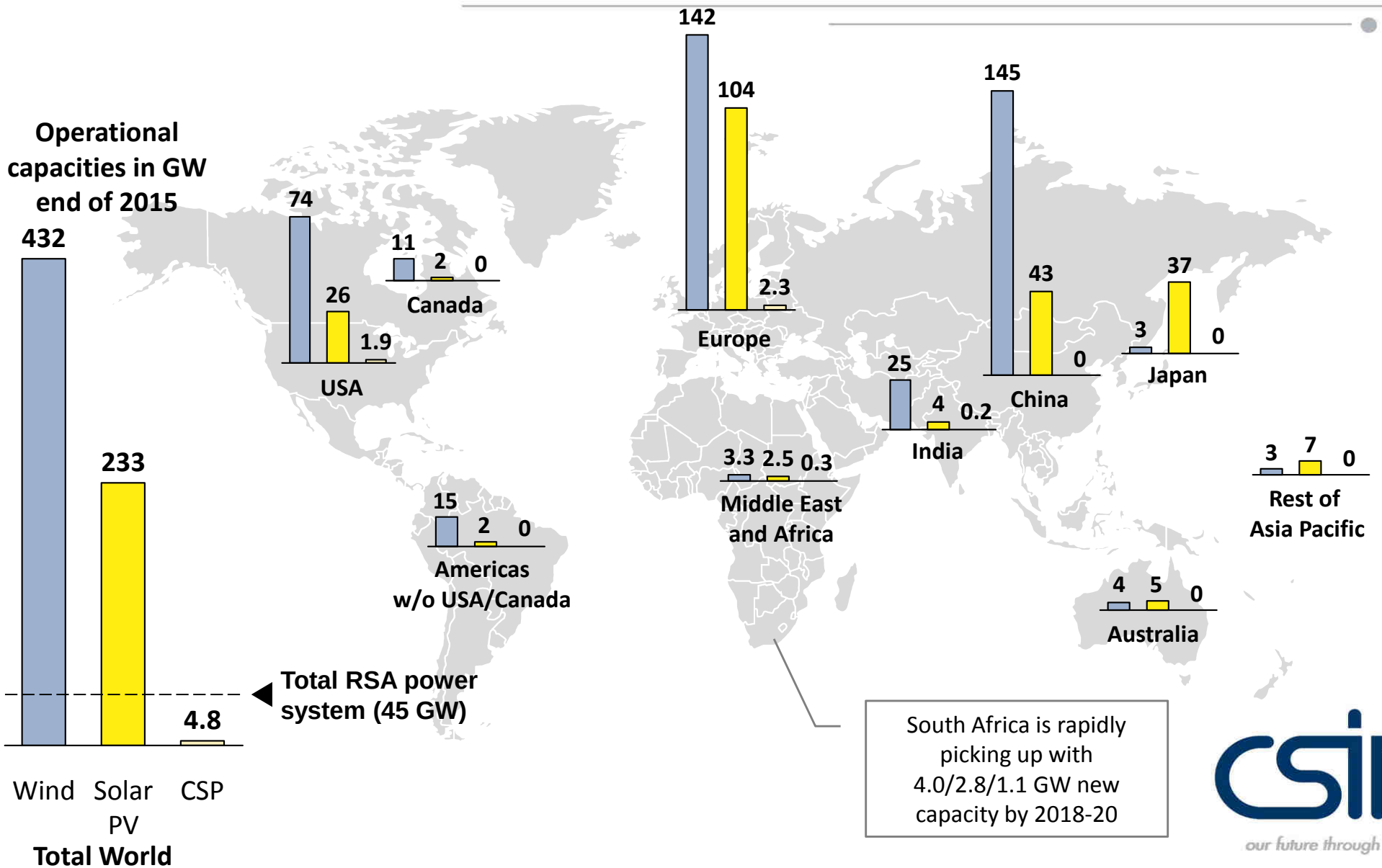


This is all very new: Almost 90% of the globally existing PV capacity was installed during the last five years alone!

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



Sources: GWEC; EPIA; CSPToday; CSIR analysis

Agenda

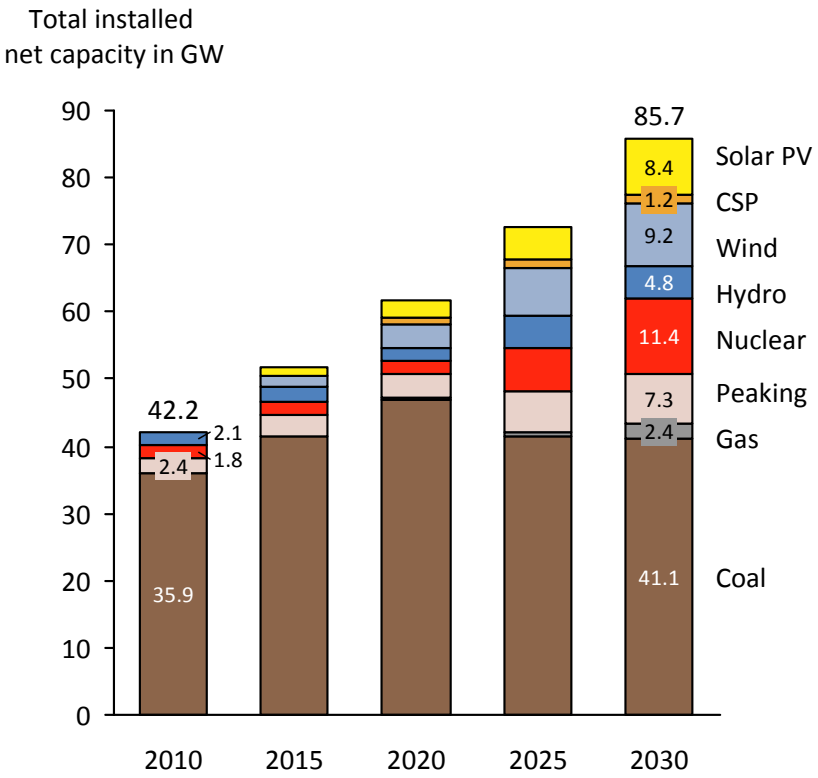
Renewables in South Africa

Wind potential in South Africa

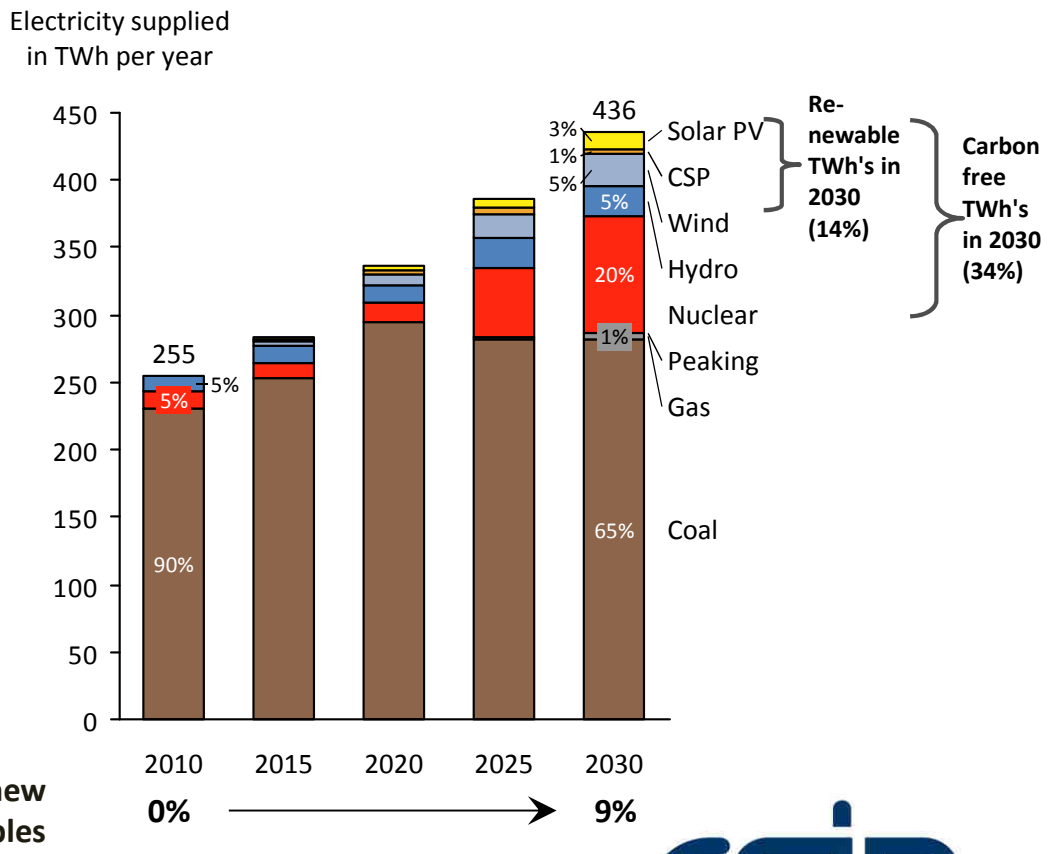
Extreme renewables scenarios

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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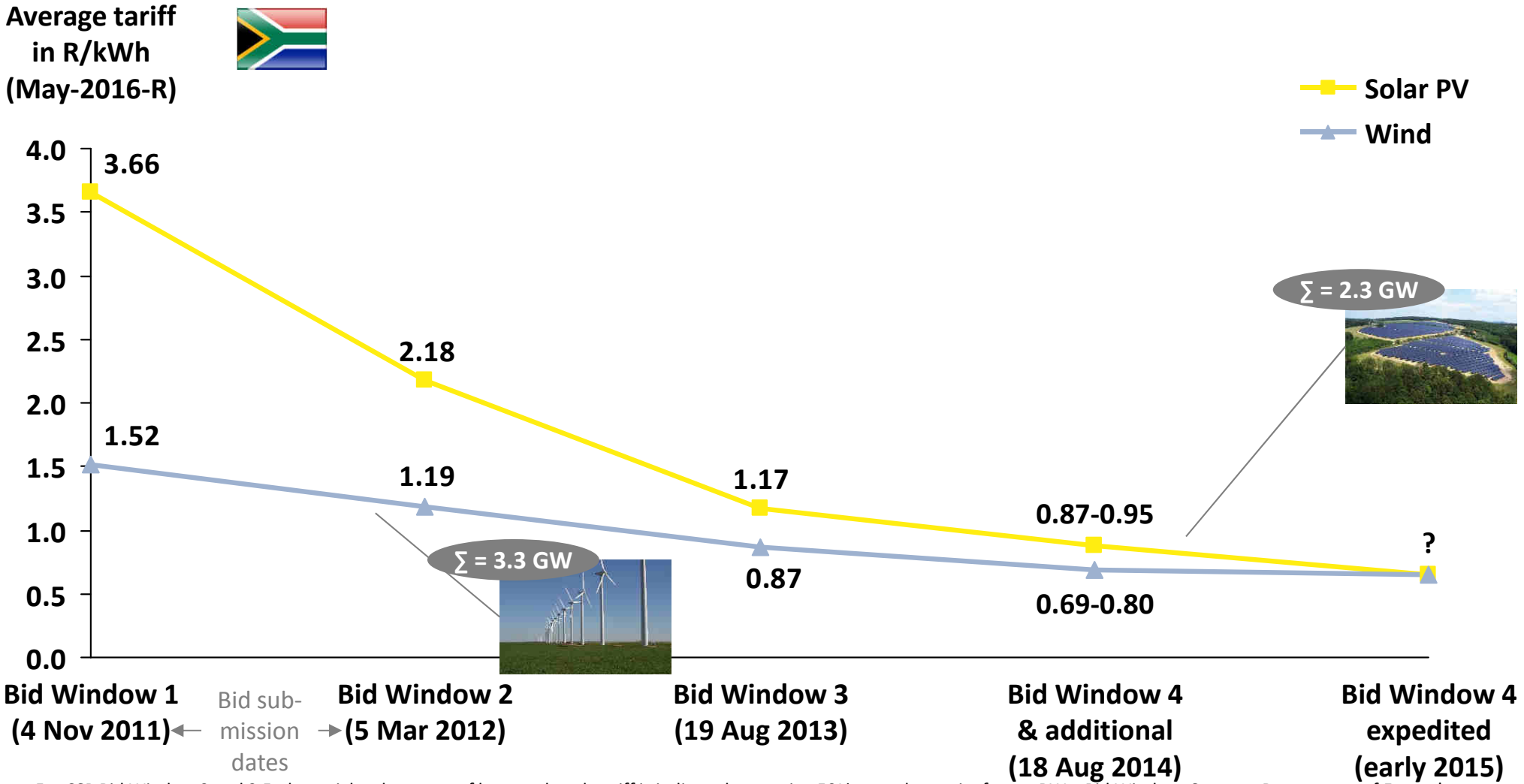
Note: hydro includes imports from Cahora Bassa

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

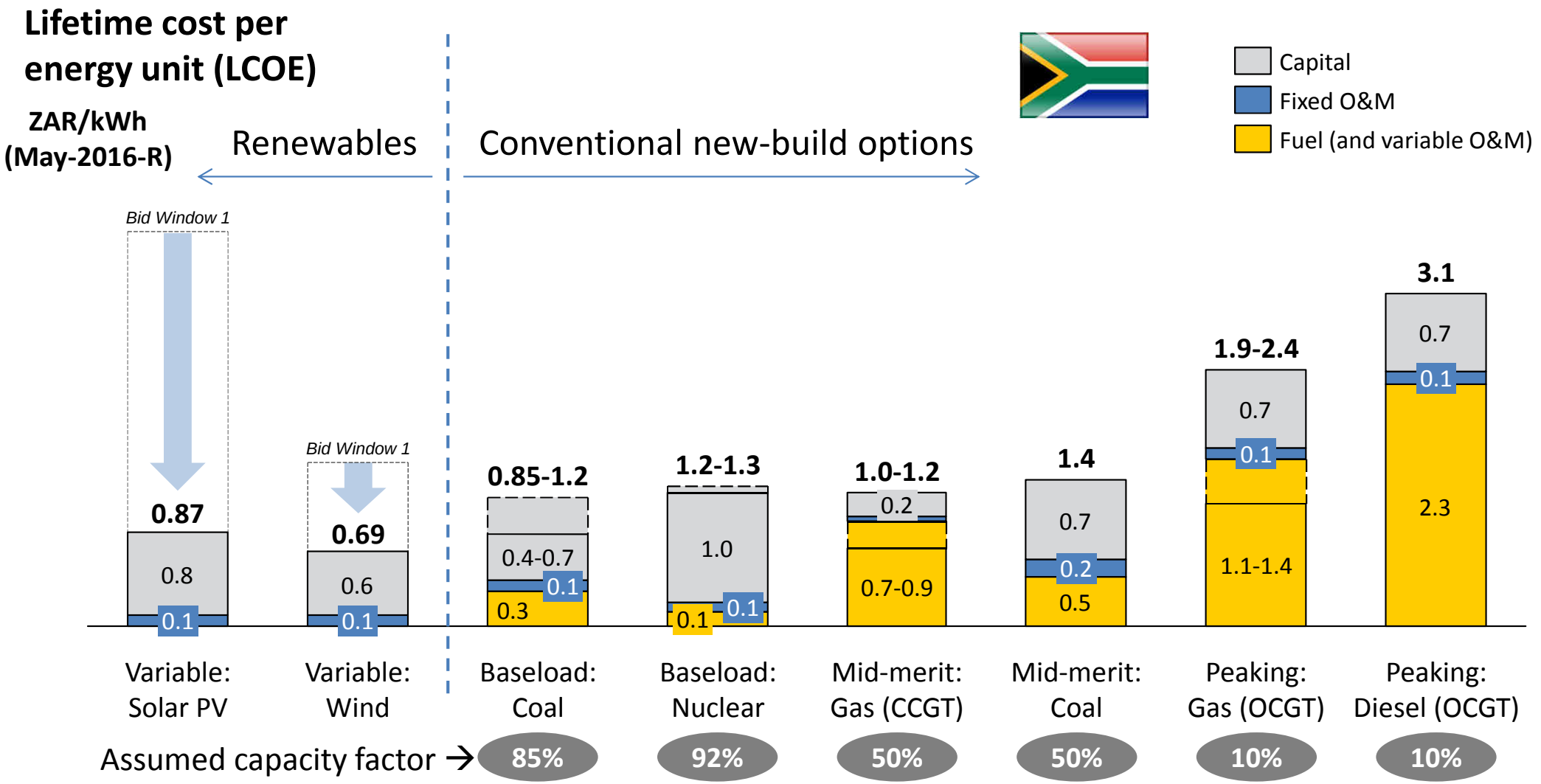
Competitive tender outcome: new wind/solar PV projects very cheap

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 capacity 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 May-2016 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; EE Publishers for Medupi and Kusile cost; CSIR analysis

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The CSIR conducted a Wind and Solar PV Resource Aggregation Study

CSIR, SANEDI, Eskom and Fraunhofer IWES conducted a joint 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

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

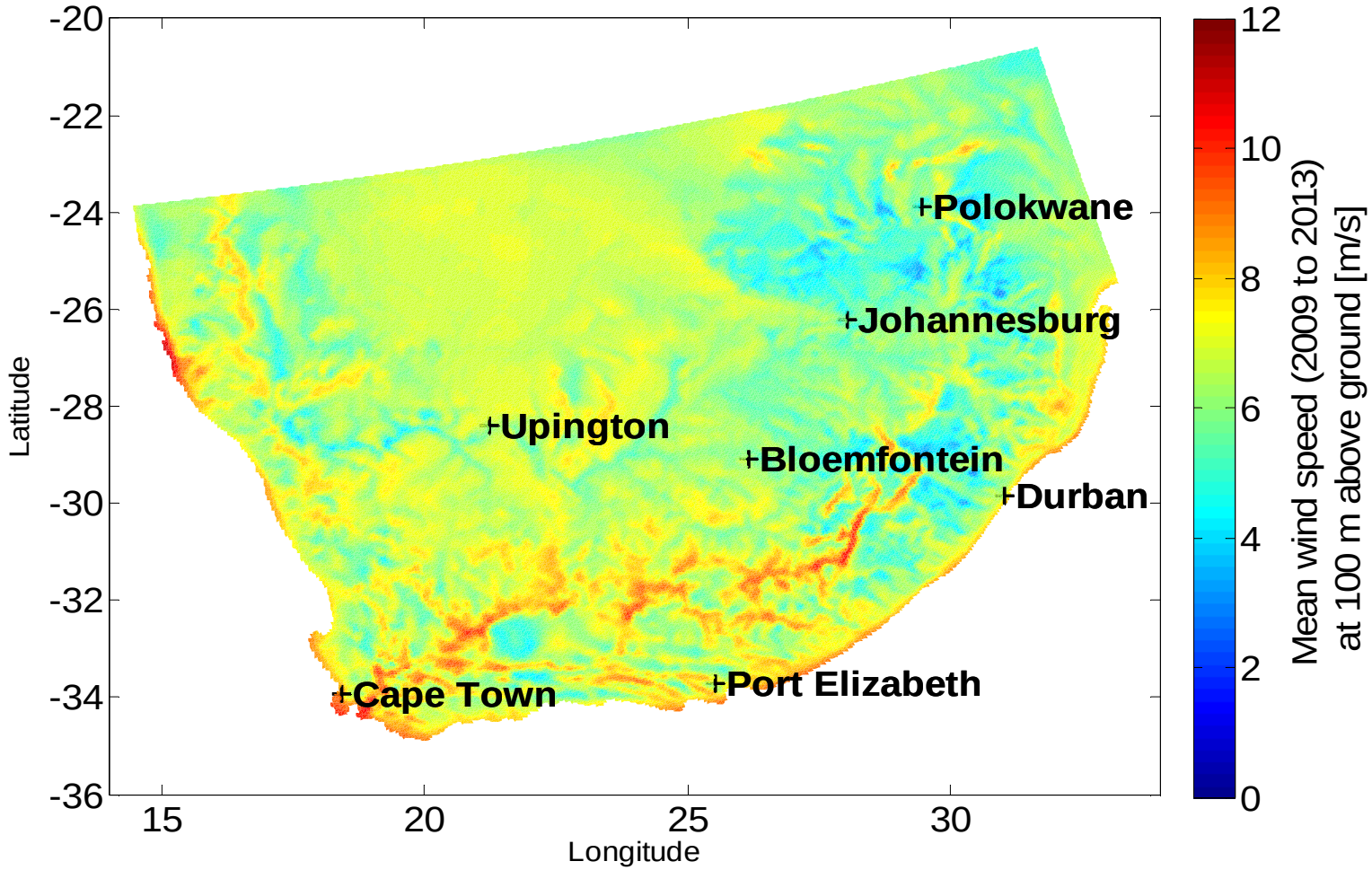
Output: Simulated time-synchronous solar PV and wind power production time-series

- 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)

Sources: www.csir.co.za/Energy_Centre/wind_solarpv.html

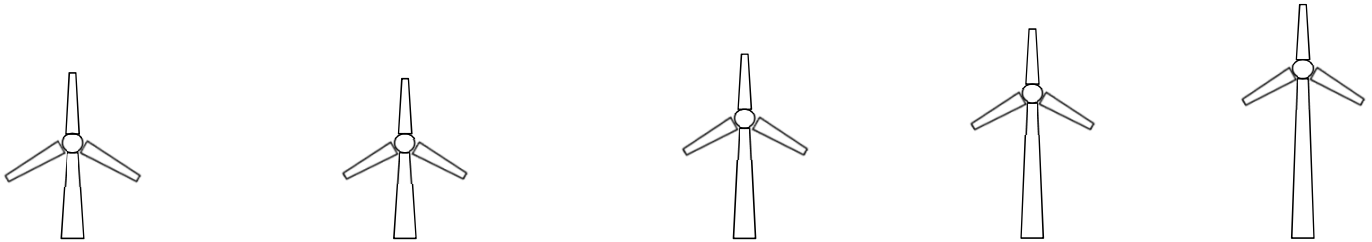
South Africa has wide areas with > 6 m/s average wind speed @ 100 m

Average wind speed at 100 meter above ground for the years from 2009-2013 for South Africa



Five different generic wind turbine types defined for simulation of wind power output per 5x5 km pixel in South Africa (~50 000 pixels)

High-wind-speed turbine ⟷ Low-wind-speed turbine



Turbine type no.	1	2	3	4	5
Nominal power [MW]	3	2.2	2.4	2.4	2.4
Selection criterion	$\bar{v}_{80m} > 8.5\frac{m}{s}$	$\bar{v}_{80m} < 8.5\frac{m}{s}$ and $\bar{v}_{100m} > 7.5\frac{m}{s}$	$\bar{v}_{100m} < 7.5\frac{m}{s}$	$\bar{v}_{120m} < 7.5\frac{m}{s}$	$\bar{v}_{140m} < 7.5\frac{m}{s}$
Blade diameter [m]	90	95	117	117	117
Hub height [m]	80	80	100	120	140

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

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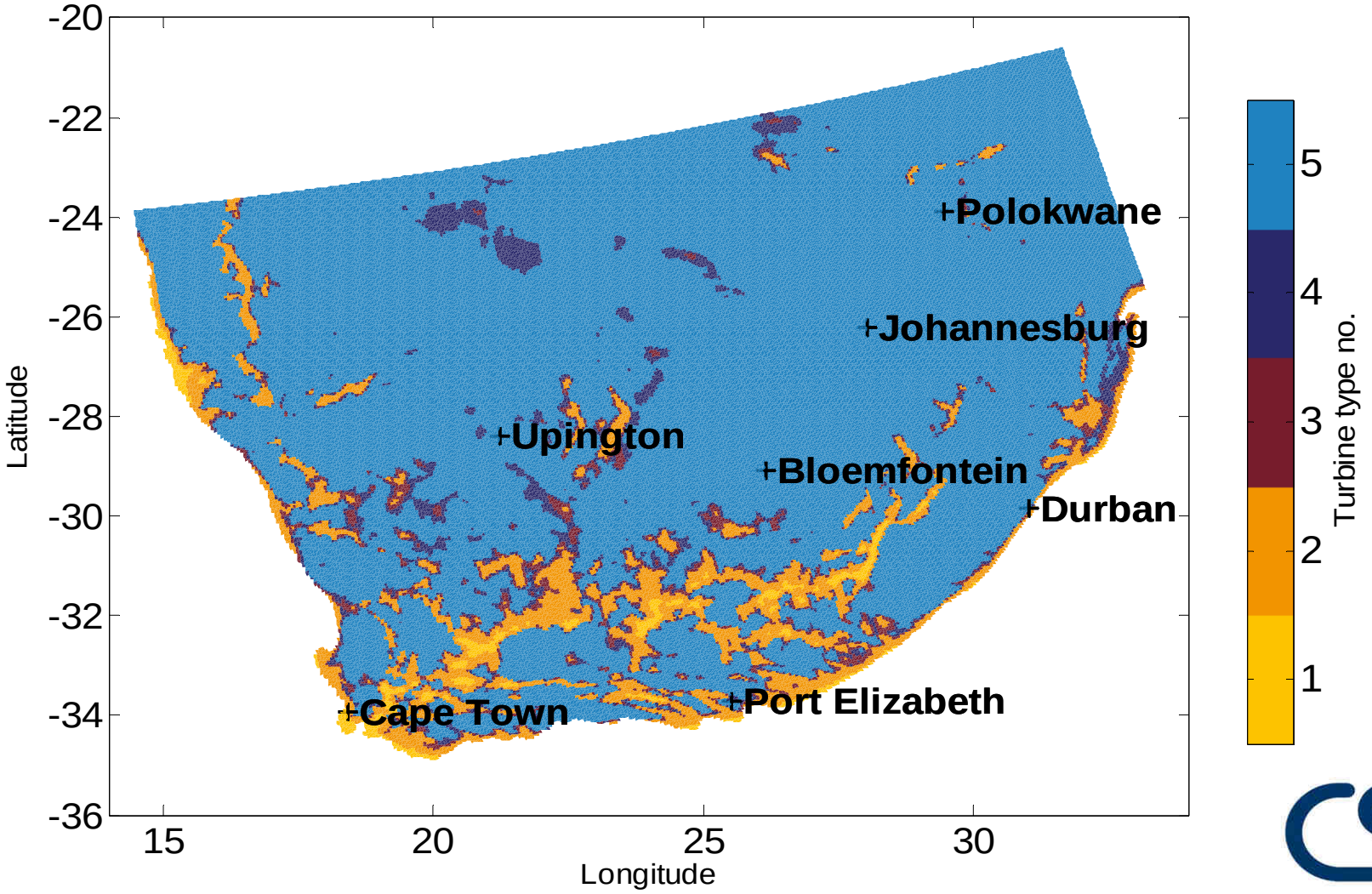
Distribution of turbine types according to mean wind speeds



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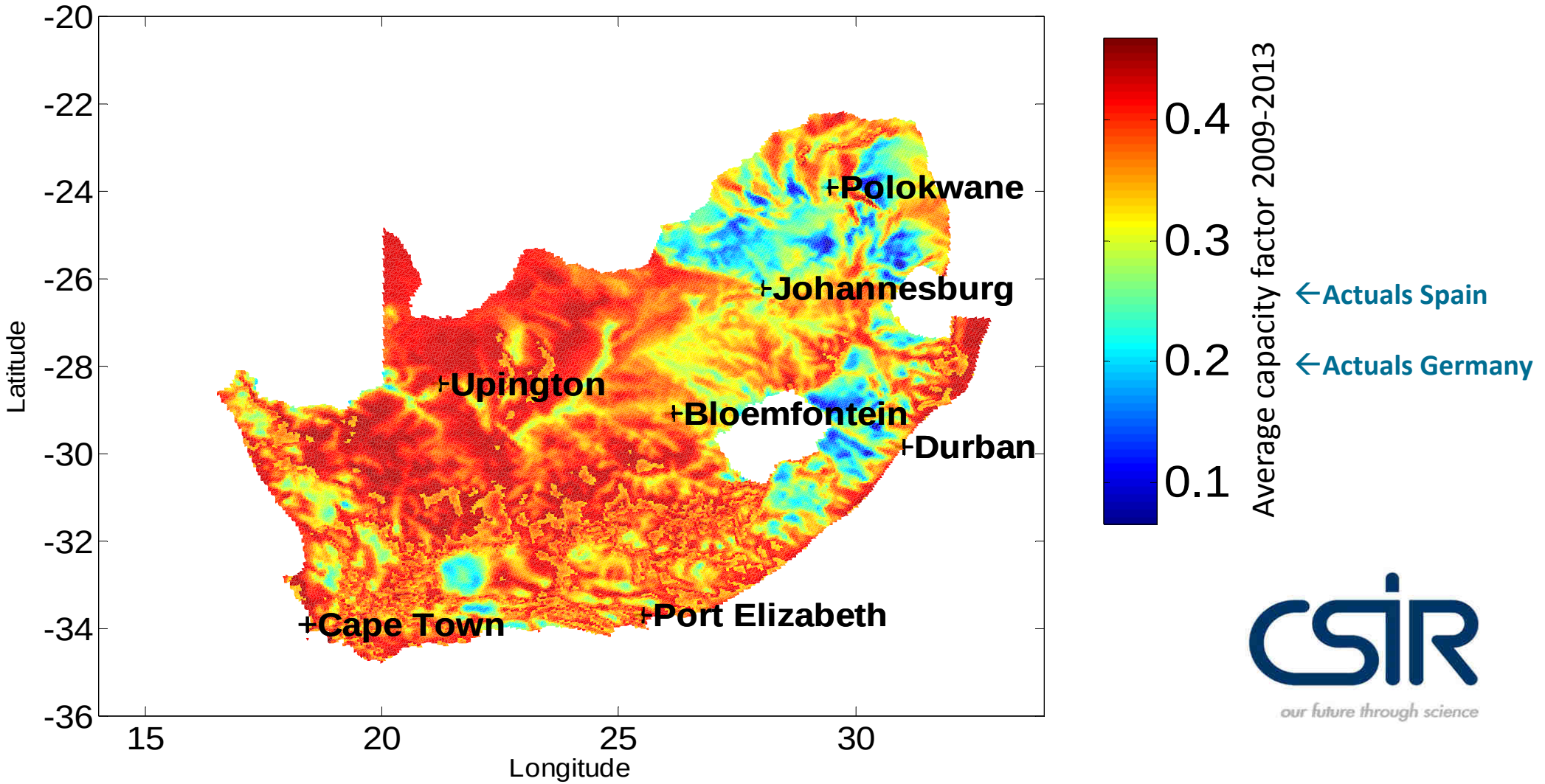
One outcome of the study:
More than 30% capacity factor achievable almost everywhere in RSA

Achievable average wind capacity factors for 2009-2013 for turbine types 1-5



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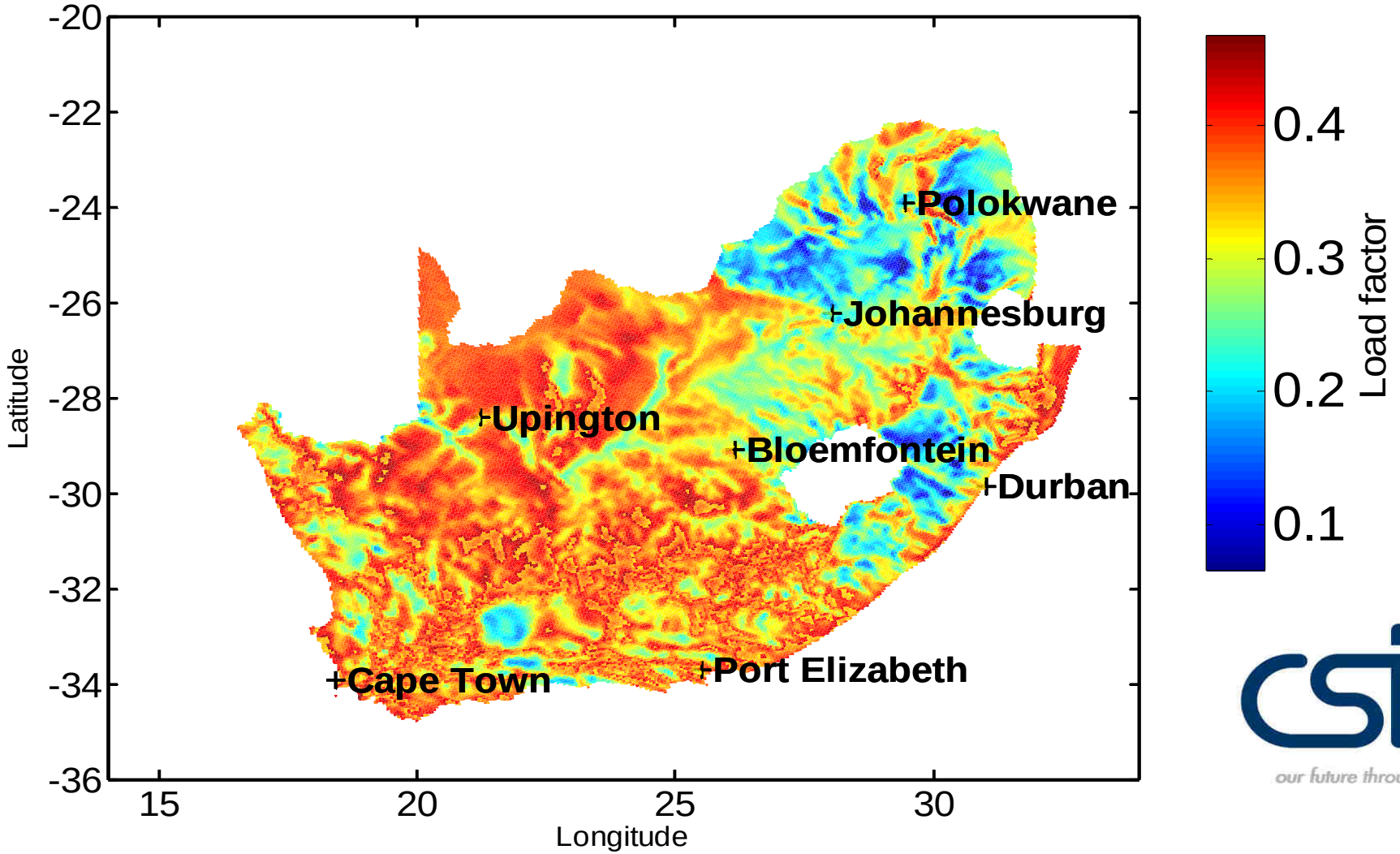
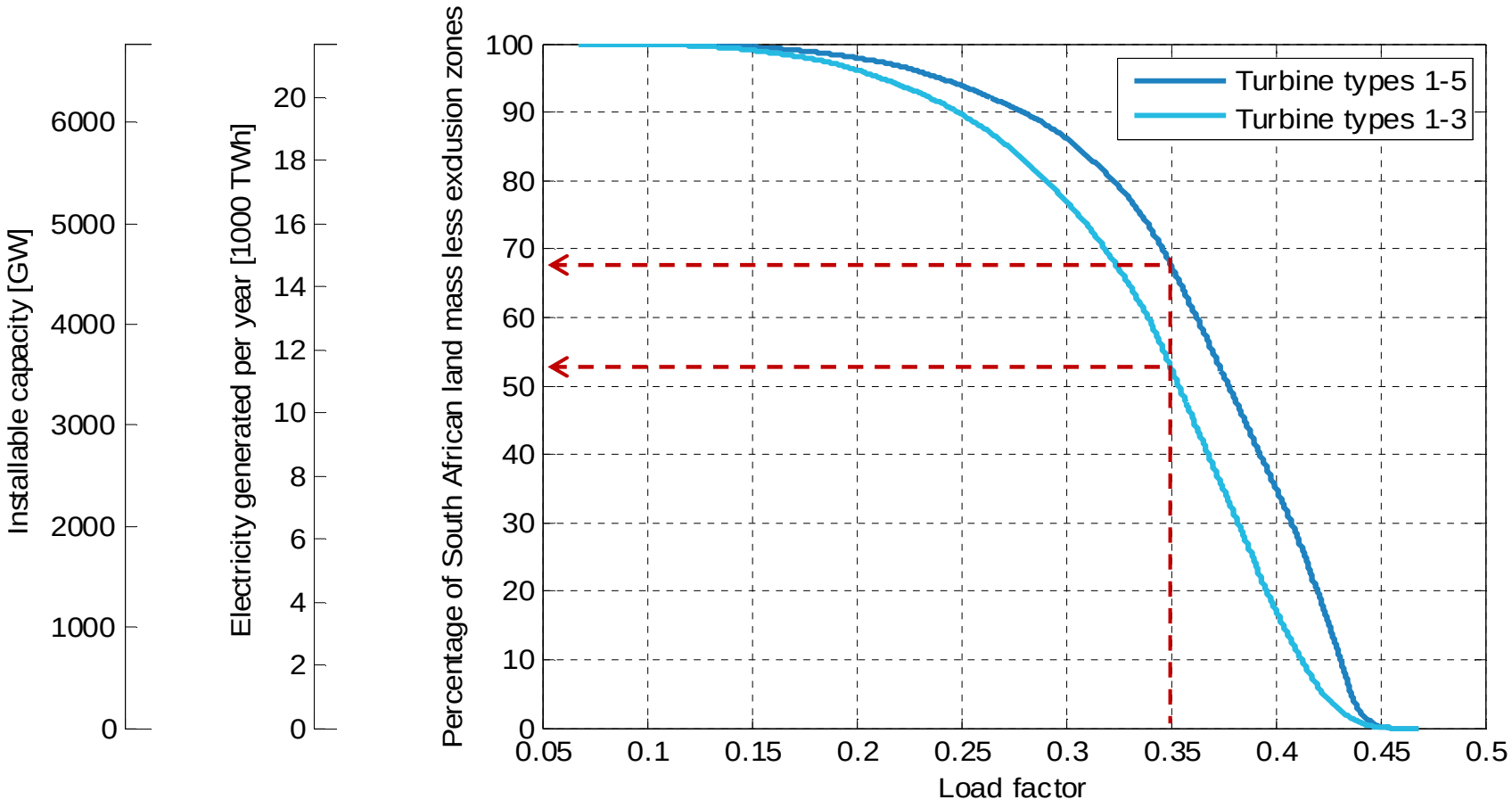
Even when placing only high-wind-speed turbine types (1, 2, 3) in each pixel shows: more than 30% capacity factor achievable in wide areas

Achievable average wind capacity factors for 2009-2013 for turbine types 1-3



On almost 70% of suitable land area in South Africa a 35% capacity factor or higher can be achieved (>50% for turbines 1-3)

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



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

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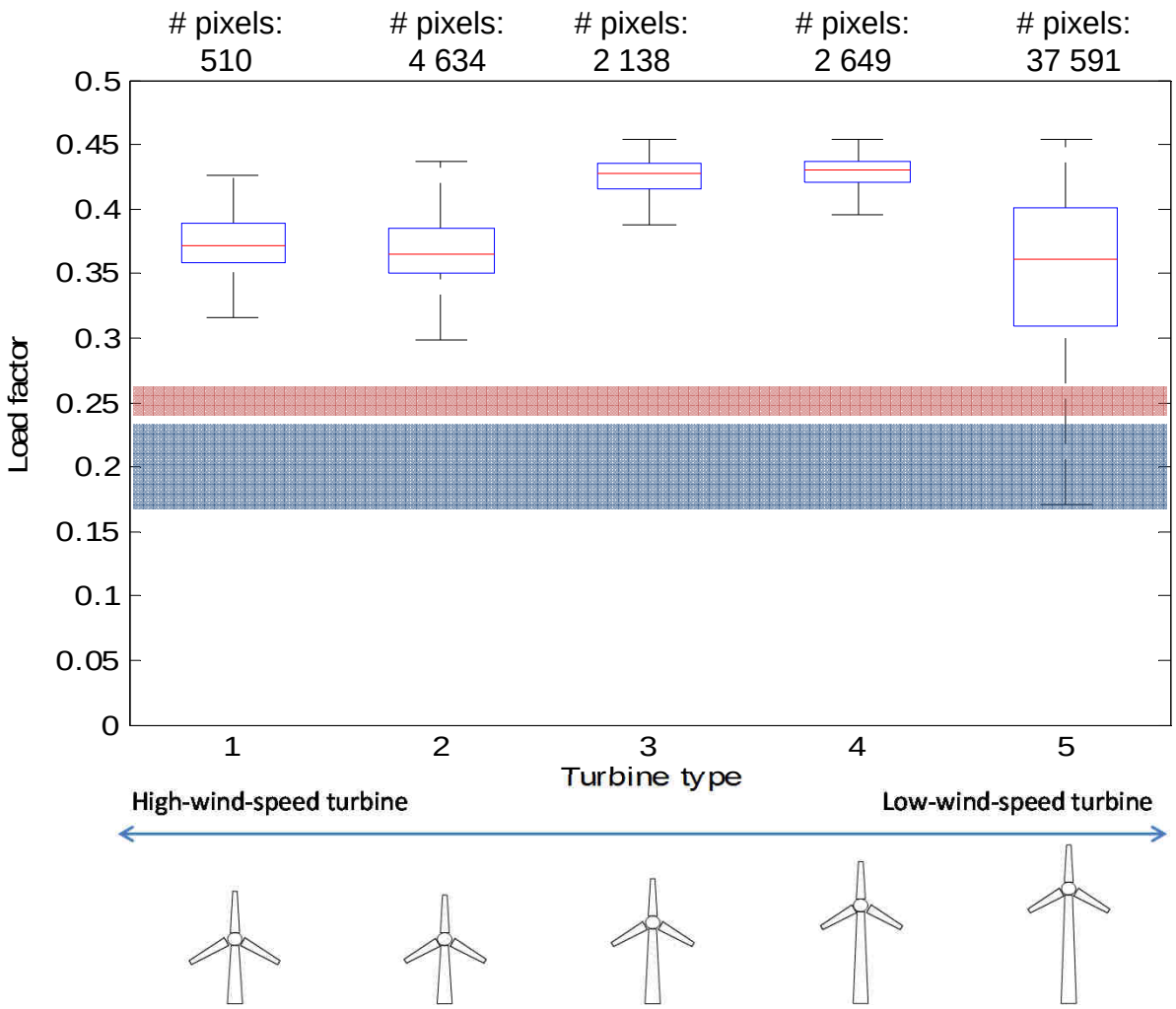
Achievable capacity factors in all turbine categories significantly higher than in leading wind countries

Achievable capacity factor distribution per pixel per turbine type



Spain (installed capacity: 23 GW)

Germany (installed capacity 46 GW)

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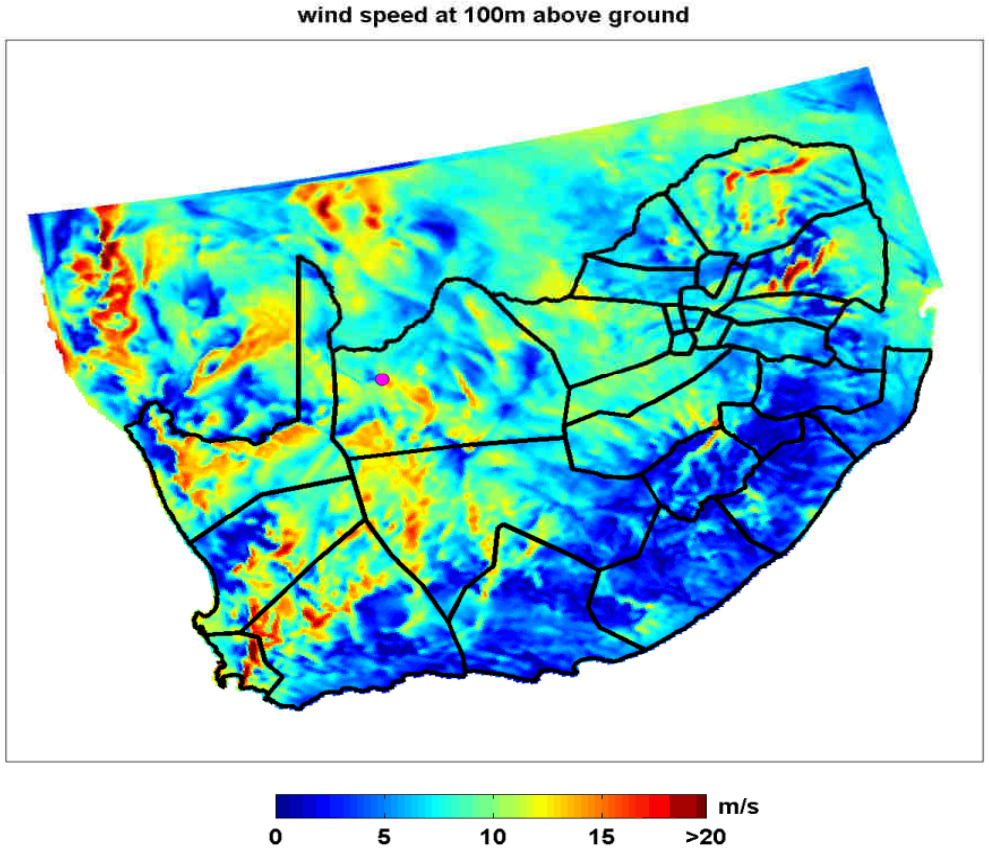
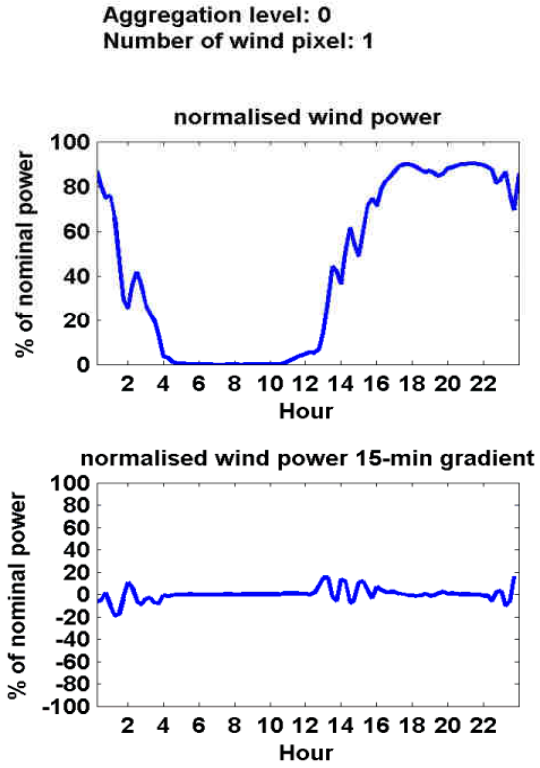
A single wind farm changes its power output quickly

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

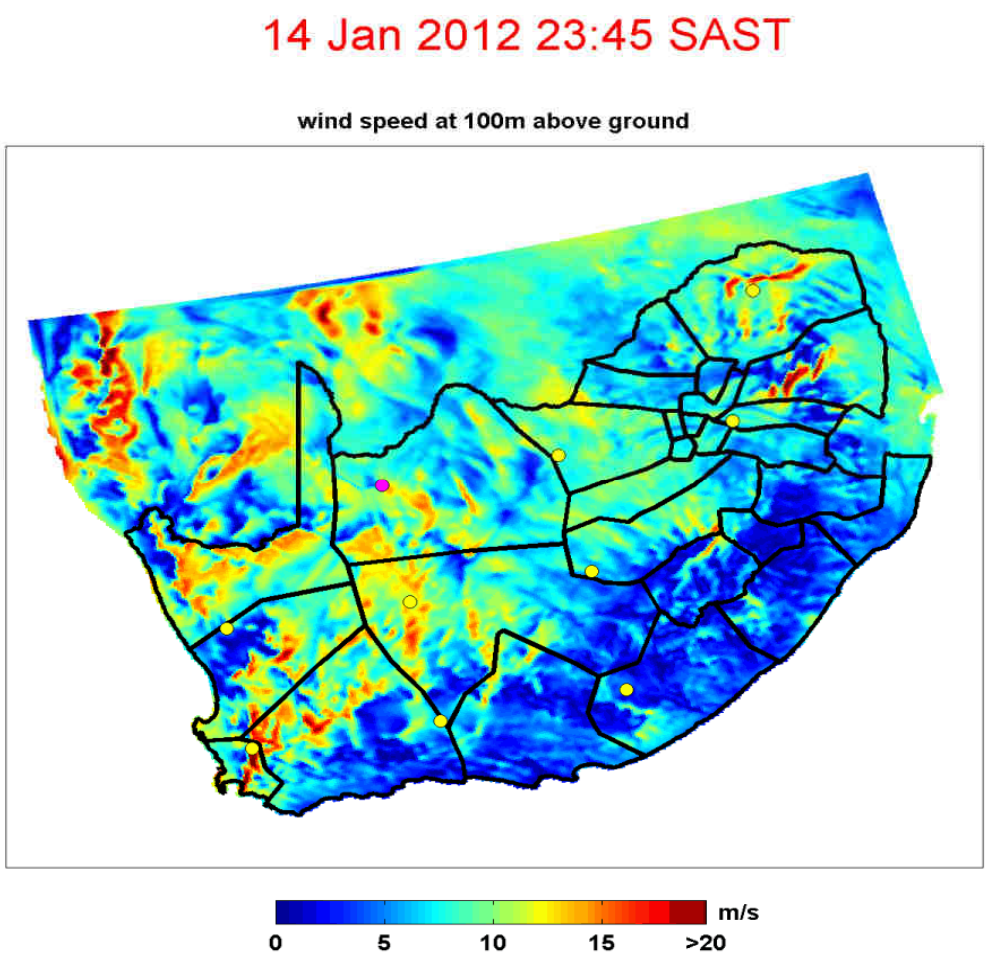
14 Jan 2012 23:45 SAST

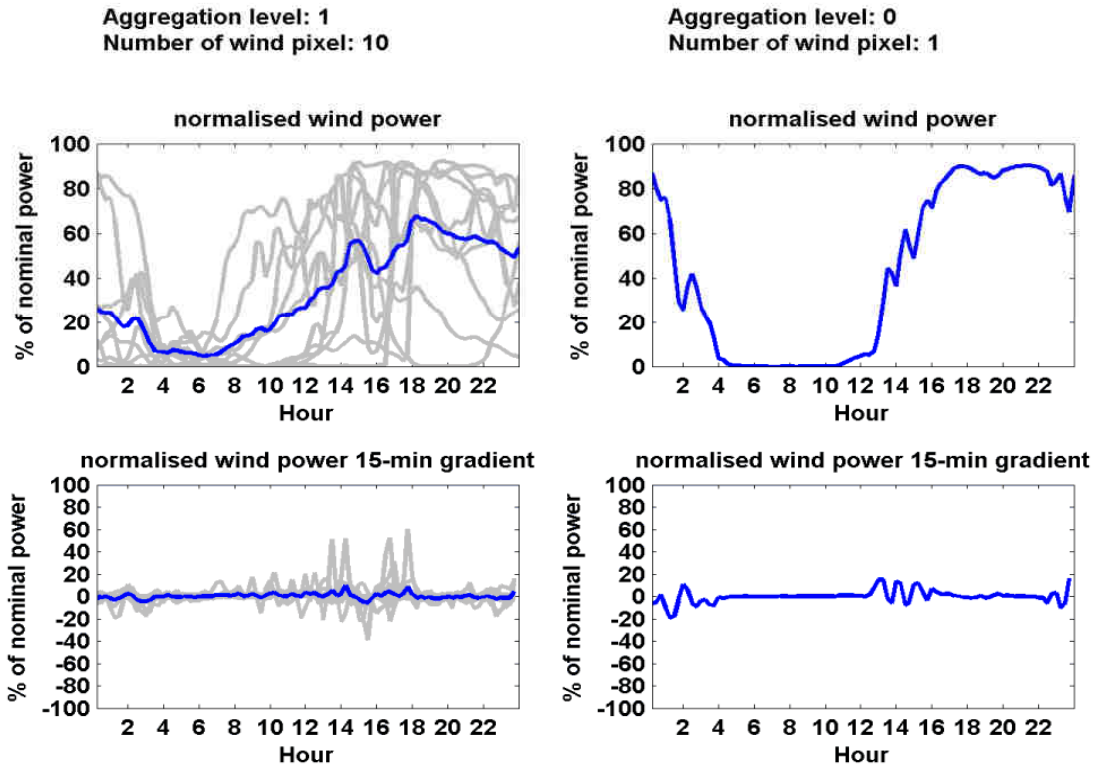




Aggregating just 10 wind farms' output reduces short-term fluctuations

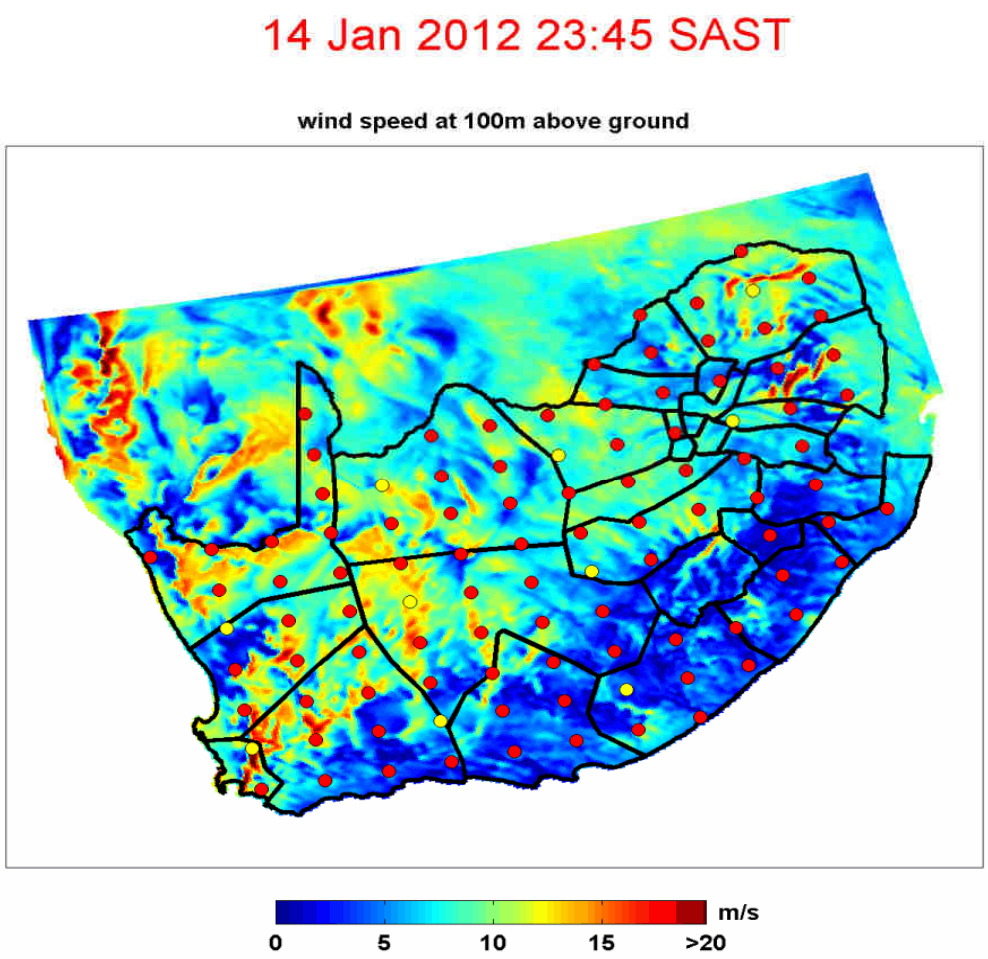
Simulated wind-speed profile and wind power output for 14 January 2012

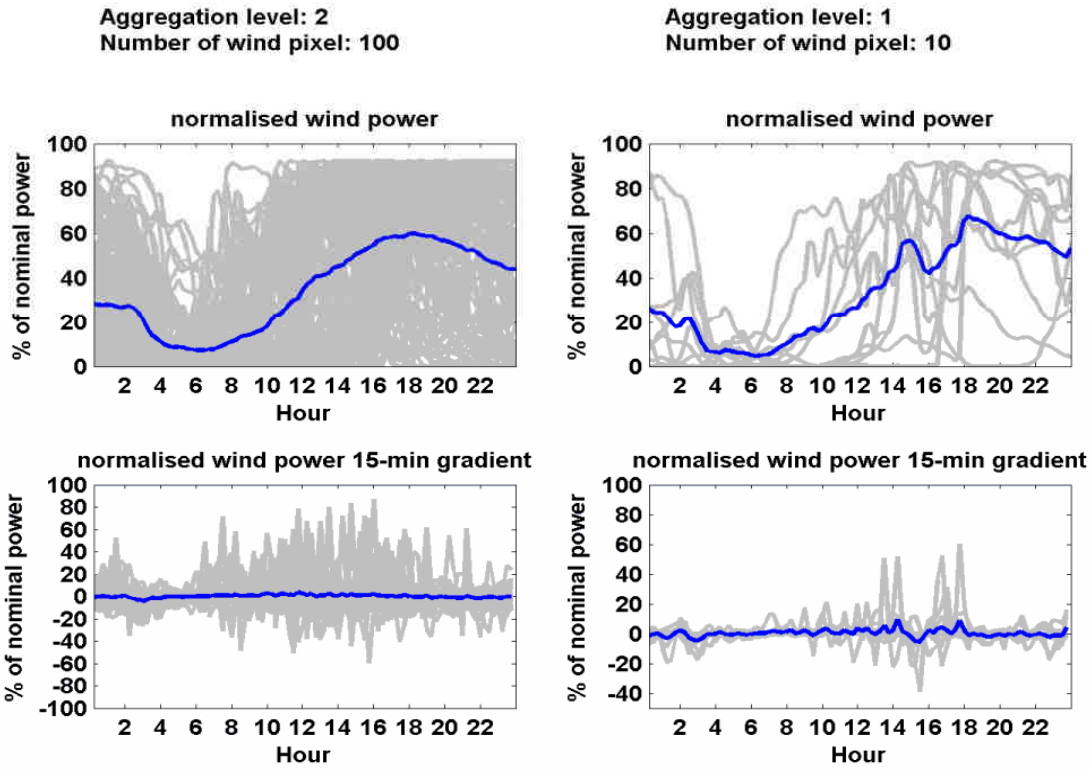




Aggregating 100 wind farms: 15-min gradients almost zero

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





Agenda

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Thought experiment: Build a new power system from scratch

Base load: **8 GW**

→ **Annual demand:** **70 TWh/yr** *(~30% of today's South African demand)*

Questions

- Technical: Can a wind & solar PV blend, mixed with flexible dispatchable power to fill gaps supply this?
- Economical: If yes, at what cost?

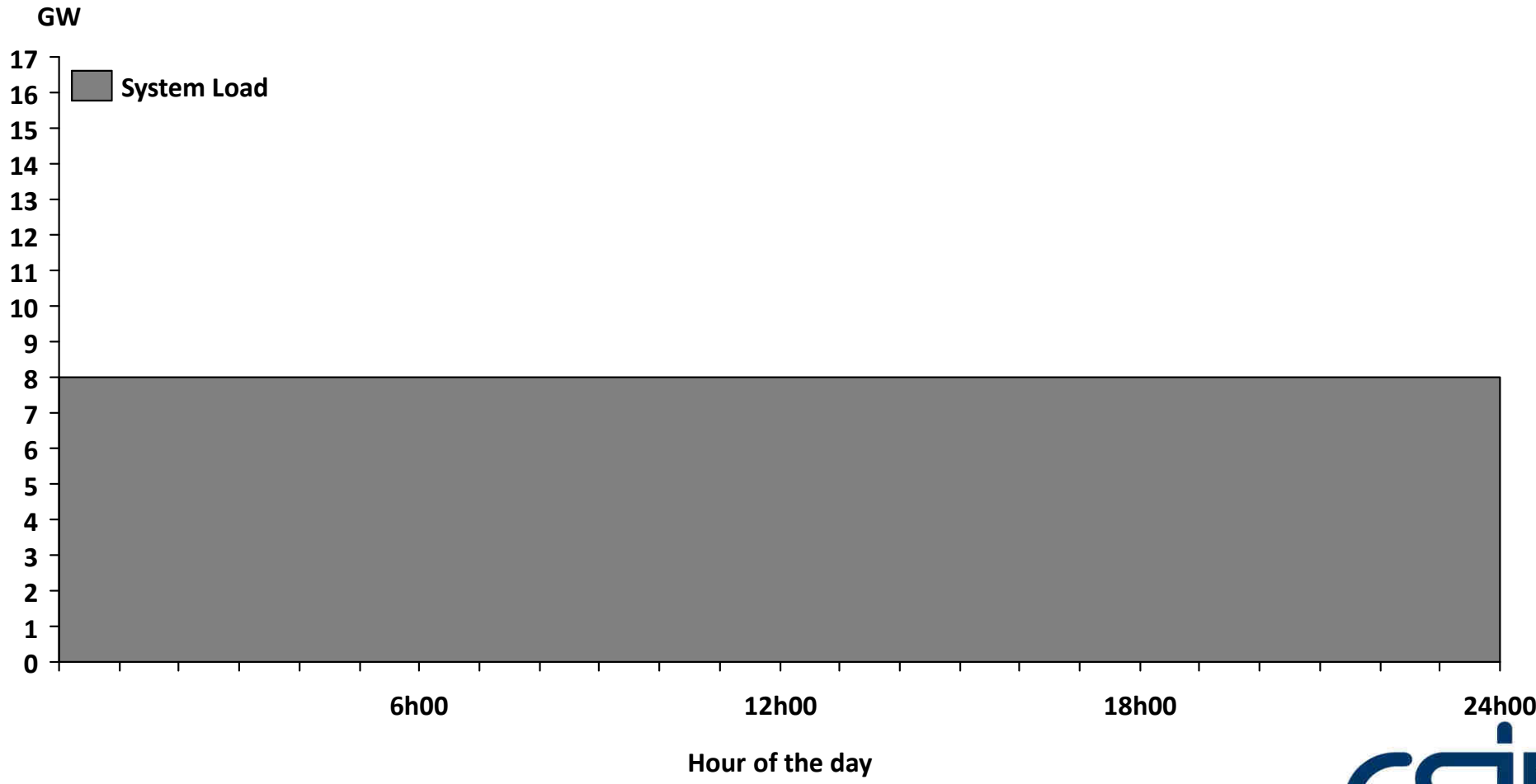
Assumptions/approach

1. 16 GW wind @ 0.69 R/kWh (Bid Window 4 average tariff in May-2016-Rand)
2. 6 GW solar PV @ 0.87 R/kWh (Bid Window 4 average tariff in May-2016-Rand)
3. 8 GW flexible power generator to fill the gaps @ 2.0 R/kWh (e.g. high-priced gas @ 11.3 $/MMBtu)

- 15-minute solar PV and wind data from recent CSIR study, covering the entire country
  - Check out the results: www.csir.co.za/Energy_Centre/wind_solarpv.html
- 15-minute simulation of supply structure for three consecutive years (2010-2012)

Notes: ZAR/USD = 14.0
Sources: IRP; REIPPPP outcomes; CSIR analysis

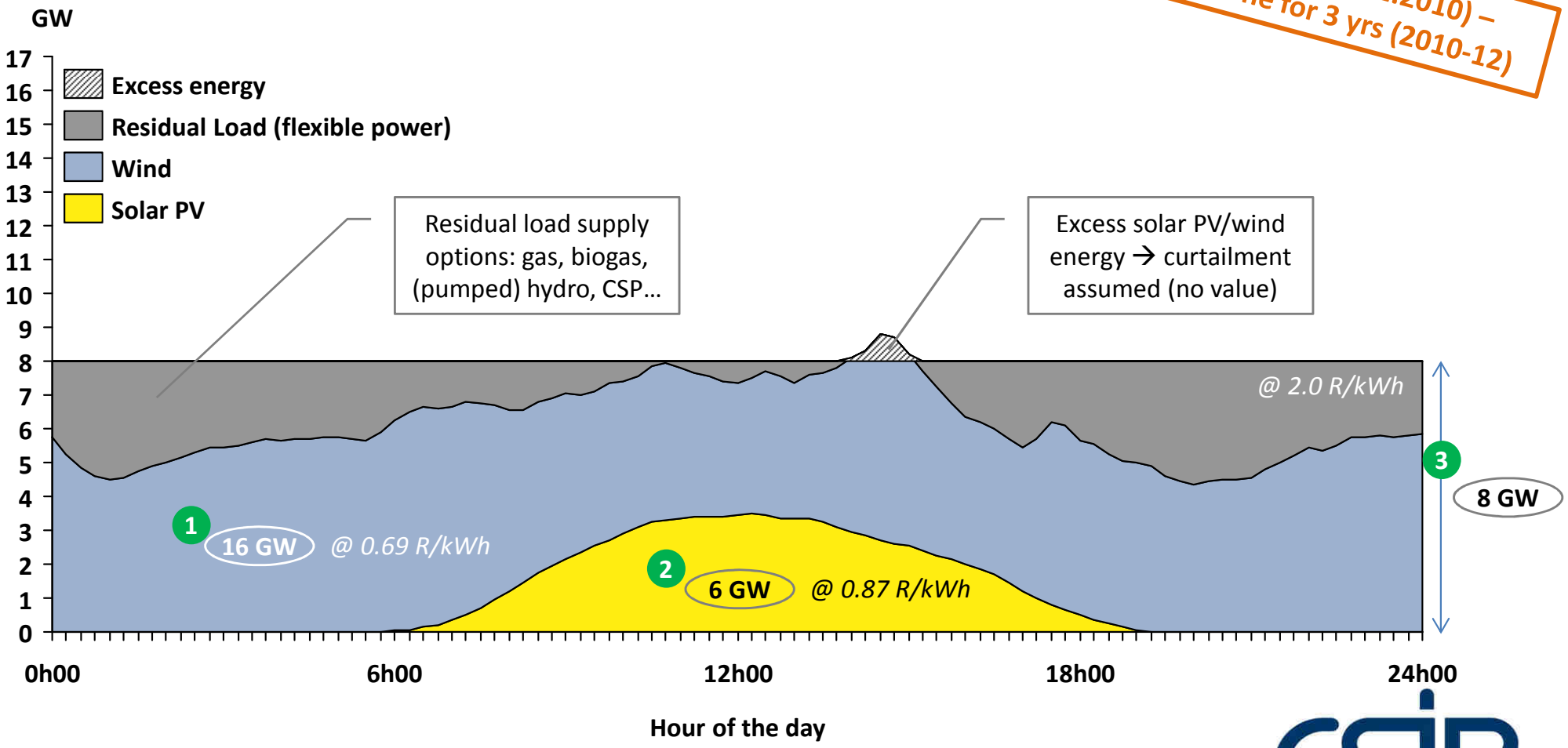
Thought experiment: assumed 8 GW of true baseload (constant load)



Sources: CSIR analysis

A mix of solar PV, wind and flexible power can supply this baseload demand in the same reliable manner as a base-power generator

One day in display (1.1.2010) – simulation done for 3 yrs (2010-12)



Total installed capacity: 30 GW to supply 8 GW baseload – does this make sense? Yes, it's about energy, not capacity!

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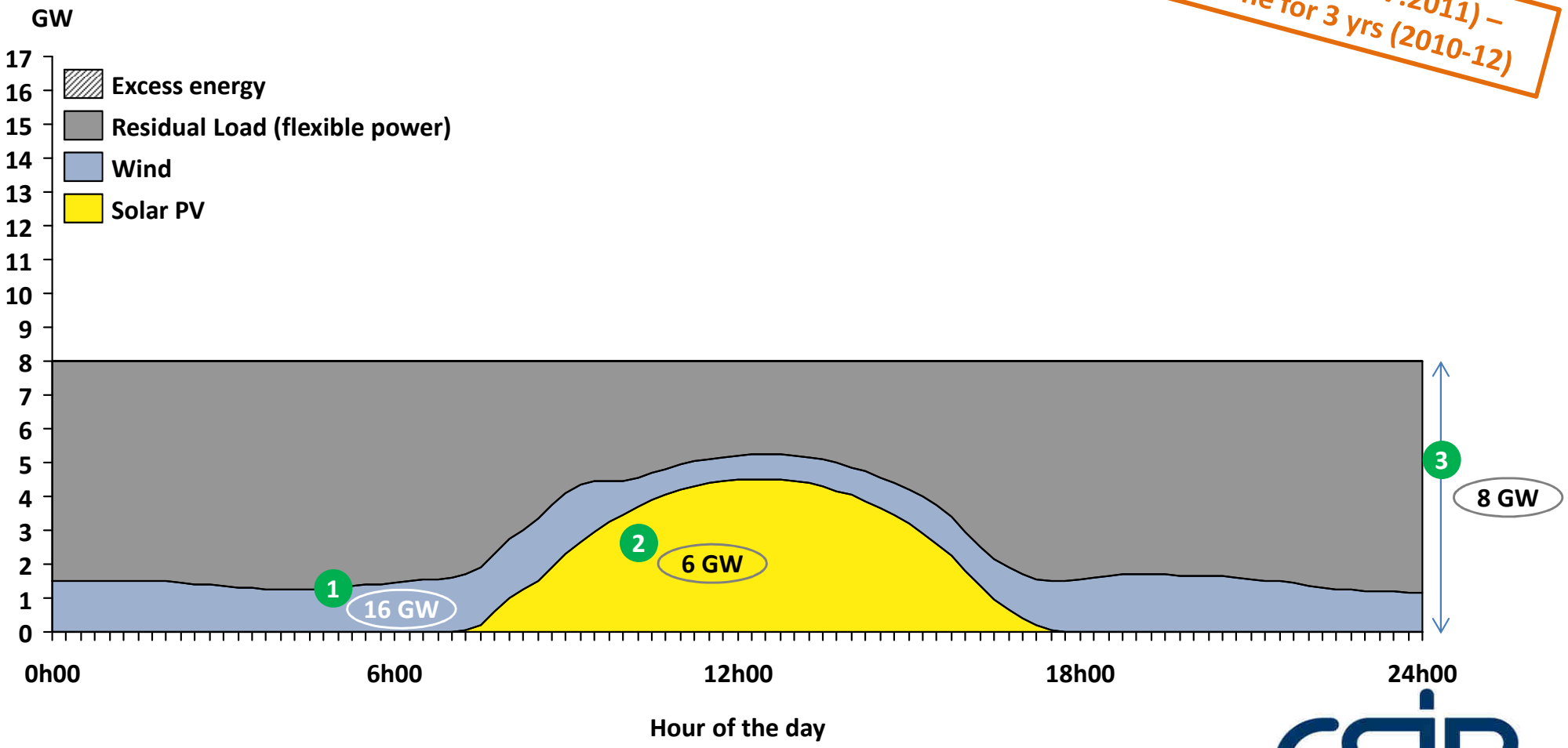
Sources: CSIR analysis

On the lowest-wind day the residual load is large

Simulated wind and solar PV power output for a 16 GW wind and 6 GW solar PV fleet on 21 July 2011

One day in display (21.7.2011) – simulation done for 3 yrs (2010-12)

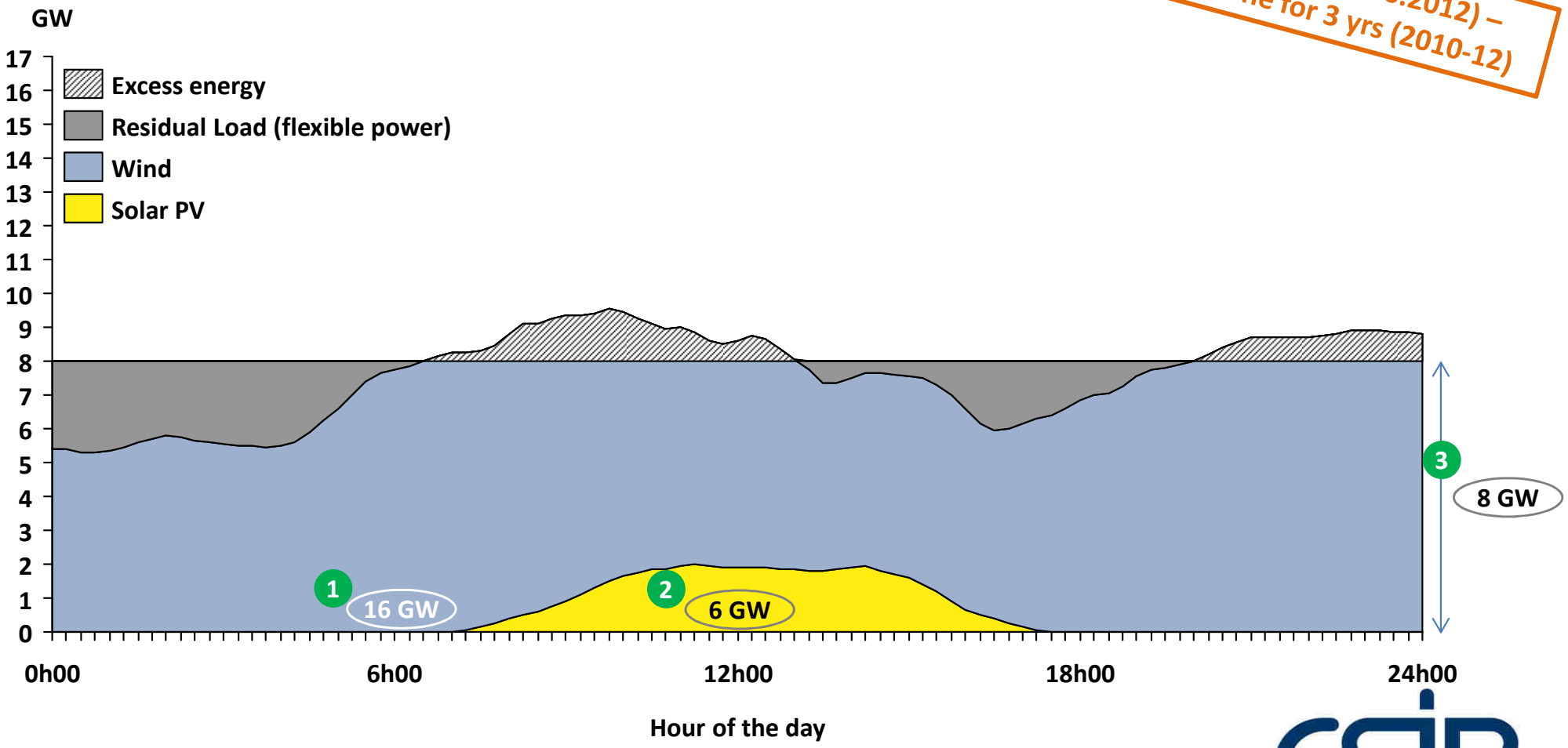


Sources: CSIR analysis

On the lowest-solar-PV day the wind fleet still contributes a lot

Simulated wind and solar PV power output for a 16 GW wind and 6 GW solar PV fleet on 21 June 2012

One day in display (21.6.2012) – simulation done for 3 yrs (2010-12)

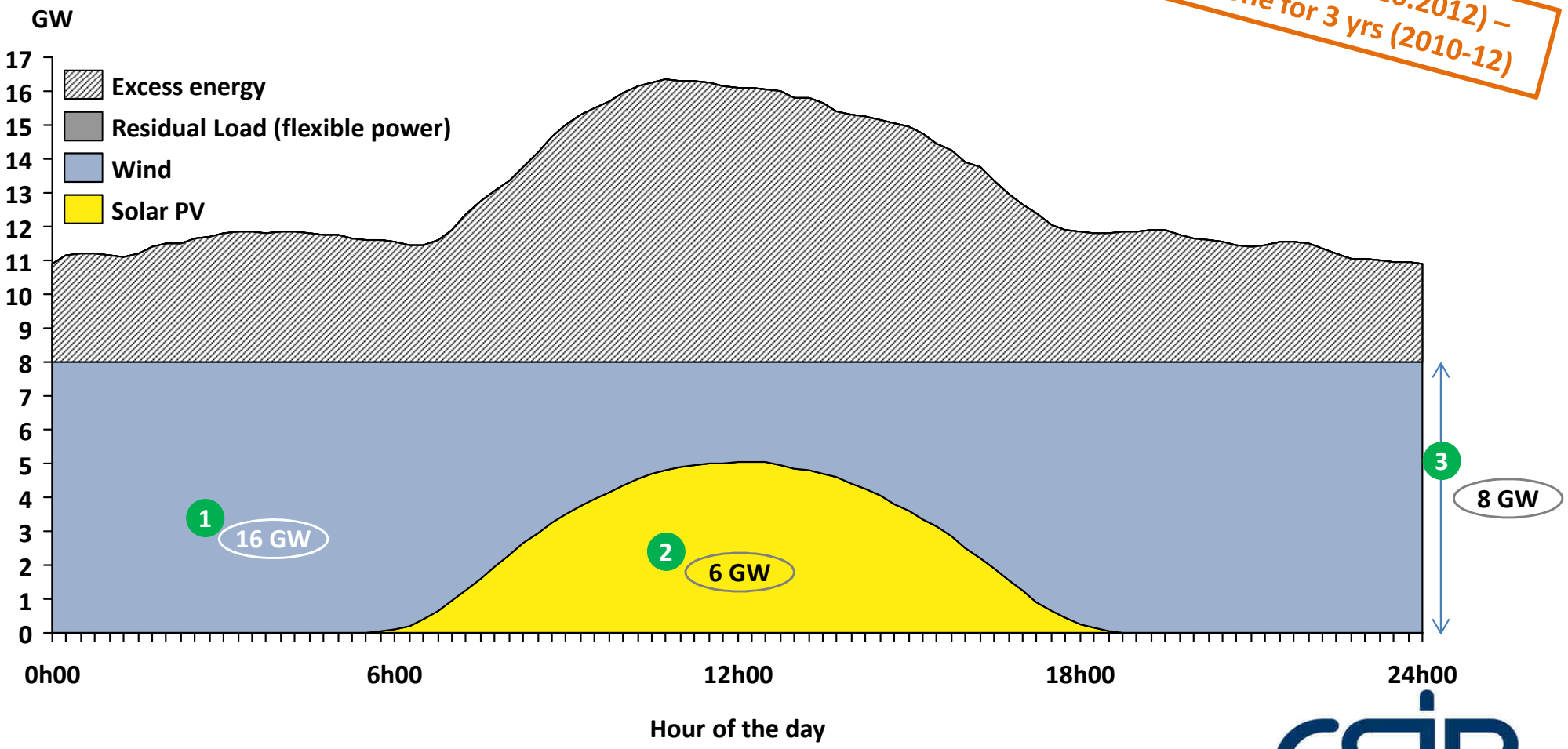


Sources: CSIR analysis

On a high-wind and solar day the amount of excess energy is large

Simulated wind and solar PV power output for a 16 GW wind and 6 GW solar PV fleet on 30 October 2012

One day in display (30.10.2012) – simulation done for 3 yrs (2010-12)

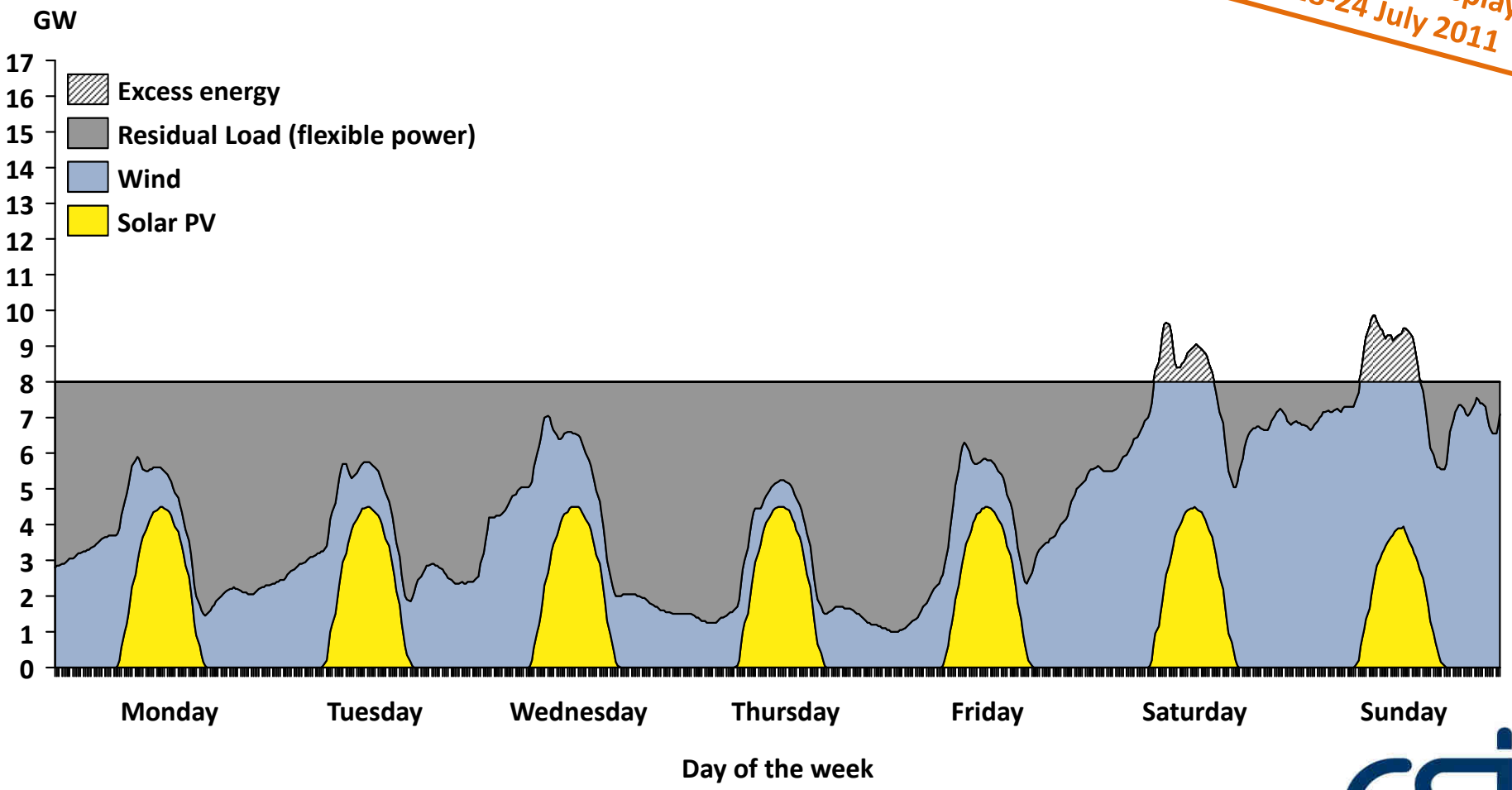


Sources: CSIR analysis

During low-wind periods, fuel for flexible generator must be stocked

Simulated 15-minute solar PV and wind power supply for the week from 18-24 July 2011

Actual week in display from 18-24 July 2011



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Sources: CSIR analysis

Technical feasibility in two key dimensions – more analyses ongoing

Ramping

- Maximum 15-minute ramp of residual load from 2010 to 2012: 0.9 GW/(15-min)
  → 12% of installed flexible capacity of 8 GW per 15-min
- Minimum 15-minute ramp of residual load from 2010 to 2012: -1.0 GW/(15-min)
  → -12% of installed flexible capacity of 8 GW per 15-min

→ Open-Cycle Gas Turbines can ramp up or down with 5-10% output change per minute

→ (Pumped) hydro plants can ramp up and down even faster

→ Plus, a down-ramp of the residual load can always be catered for by short curtailment of wind/PV

Fuel-storage

- The flexible power generator of 8 GW installed capacity requires a fuel-storage capacity of 13 days

→ Eskom currently stocks coal at power stations for more than 50 days on average

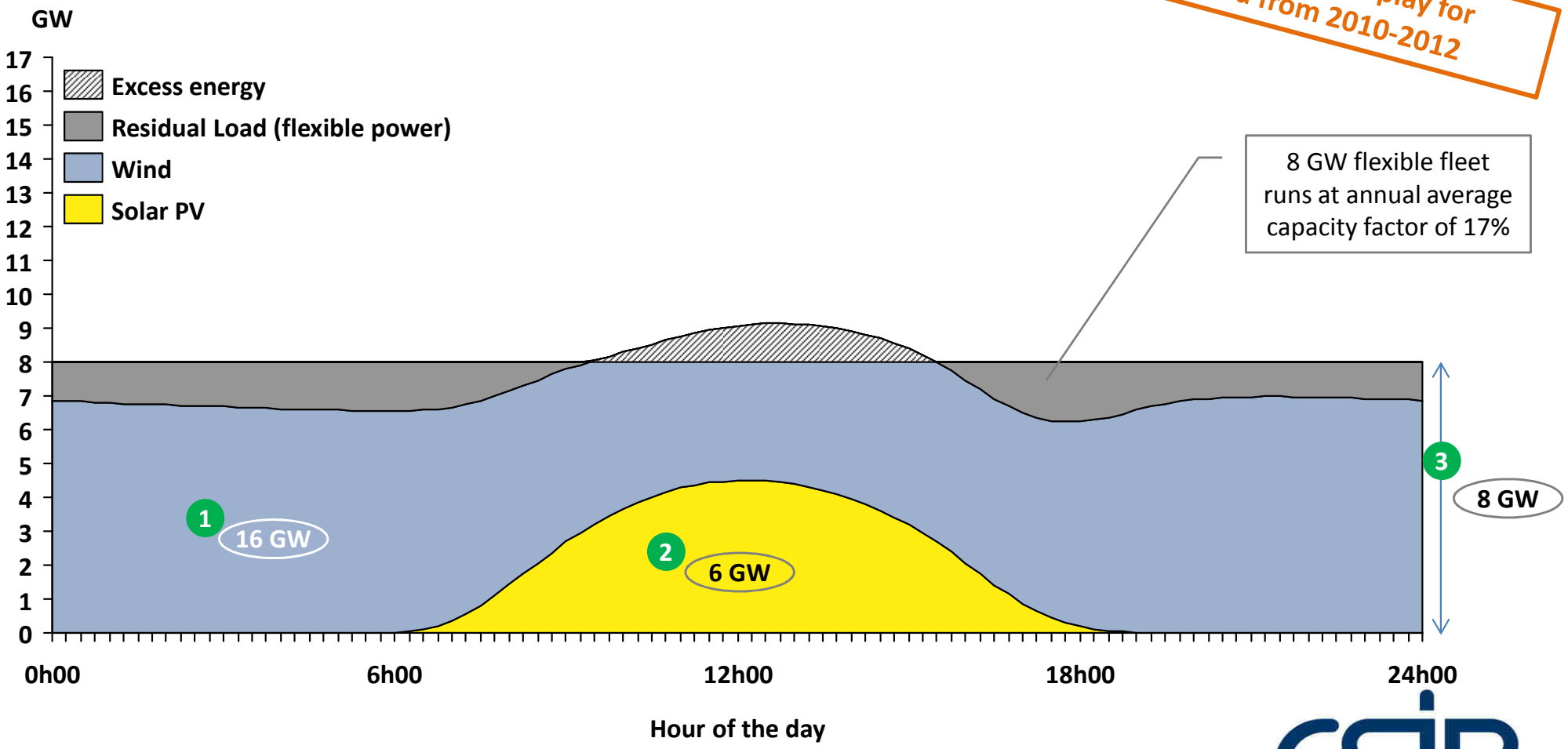
→ Buffer capacity of a LNG landing terminal is 4-6 weeks at the minimum

Additional analyses required: stable operations of power-electronics-based power systems

On average, solar PV and wind supplies 83% of the total demand

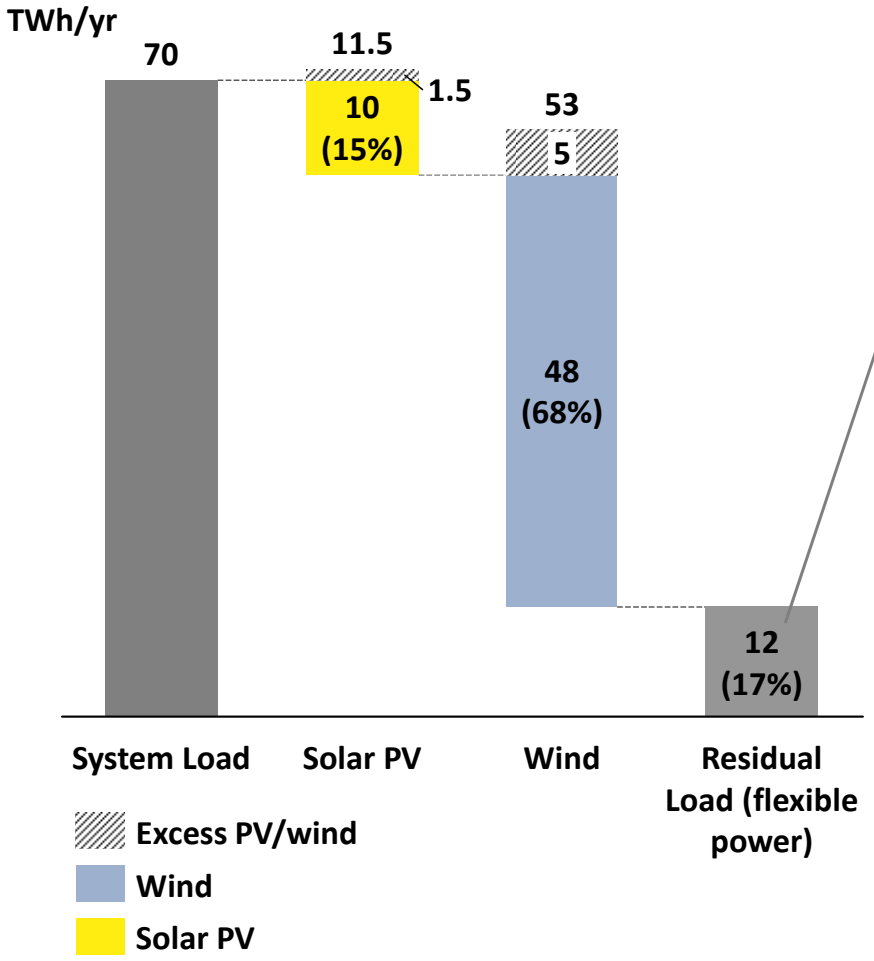
Average 15-minute solar PV and wind power supply calculated from simulation for 3 years from 2010-2012

"Average day" in display for the period from 2010-2012



Sources: CSIR analysis

Mix of solar PV, wind and expensive flexible power costs 1 R/kWh (excess thrown away) – same level as alternative baseload new-builds



Requires ~110-130 PJ/yr of natural gas → 2 mmtpa of LNG-based natural gas; roughly what Sasol converts to liquid fuels today

New-build baseload coal: 0.85-1.16 R/kWh

11.5 TWh/yr * 0.87 R/kWh
+ 52.6 TWh/yr * 0.69 R/kWh
+ 12.1 TWh/yr * 2.00 R/kWh

= 1.01 R/kWh

70.1 TWh/yr

Pessimistic assumptions

- No value given to 6.1 TWh/yr of excess energy (bought and "thrown away")
- Bid Window 4 costs for PV/wind (no further cost reduction assumed)
- Very high cost for flexible power of 2.00 R/kWh assumed

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Sources: EE Publishers; CSIR analysis

The mix of solar PV, wind and a variable power generator would cost R69 billion per year – R52 billion fixed cost and R17 billion variable

Solar PV and Wind

Annual Solar PV tariff payments (fixed):	11.5 TWh/yr * 0.87 R/kWh =	R10.0 billion/yr
Annual wind tariff payments (fixed):	52.6 TWh/yr * 0.69 R/kWh =	R36.3 billion/yr

Flexible power generators

Annualised CAPEX and fixed O&M (fixed):		R7.3 billion/yr
Fuel cost and variable O&M (variable):	12.1 TWh/yr * 1.40 R/kWh =	R17.0 billion/yr

Total

Fixed cost:	(R10.0 + R36.3 + R7.3) billion/yr =	R53.6 billion/yr
Variable cost:		R17.0 billion/yr

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Total **R70.6 billion/yr**

Flexible power generator @ 17% capacity factor: assuming 0.6 R/kWh to be fixed (capital and fixed O&M) and 1.4 R/kWh variable (fuel)

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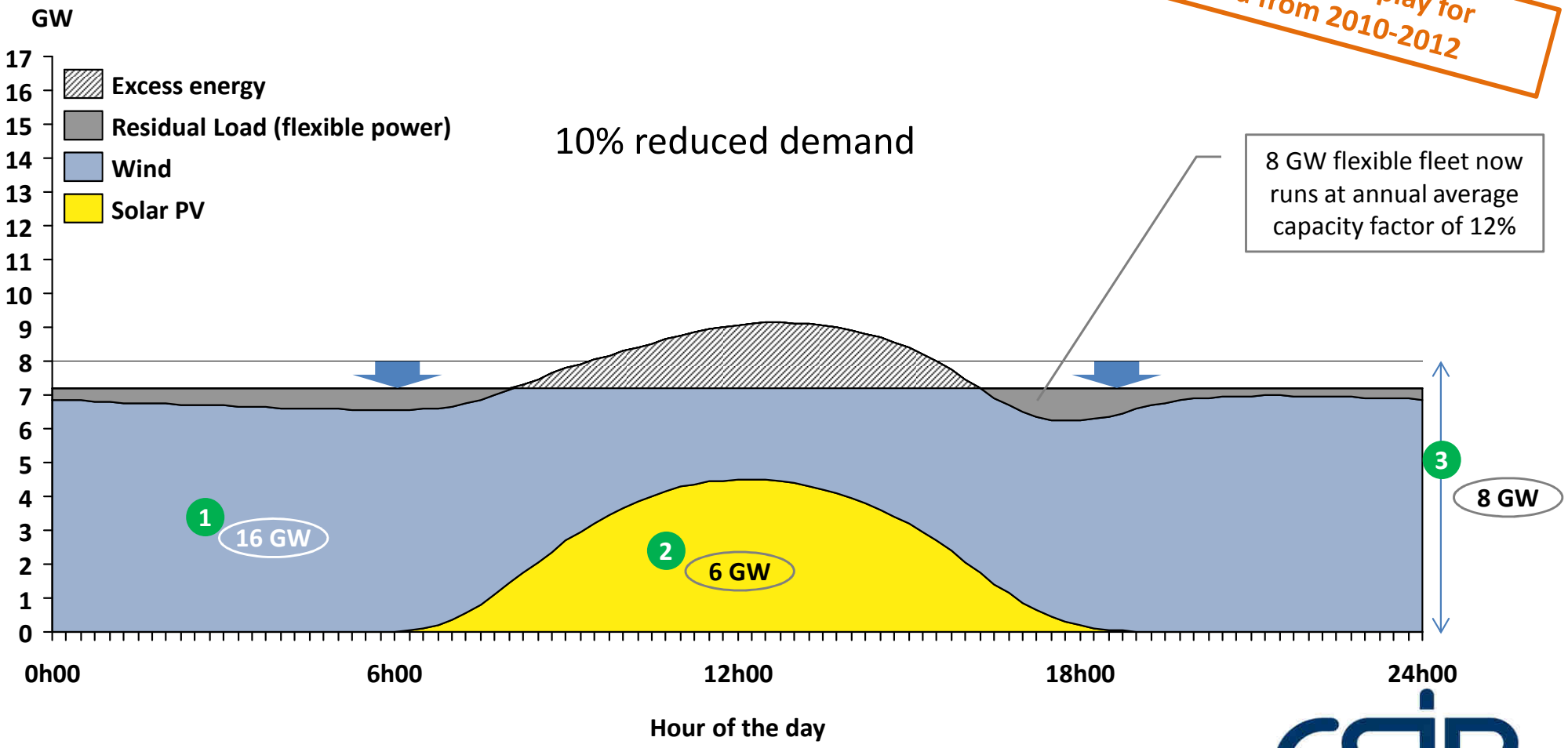
10% less load: excess energy increases, need for flexible power reduces

Average hourly solar PV and wind power supply calculated from simulation for the entire year

"Average day" in display for the period from 2010-2012



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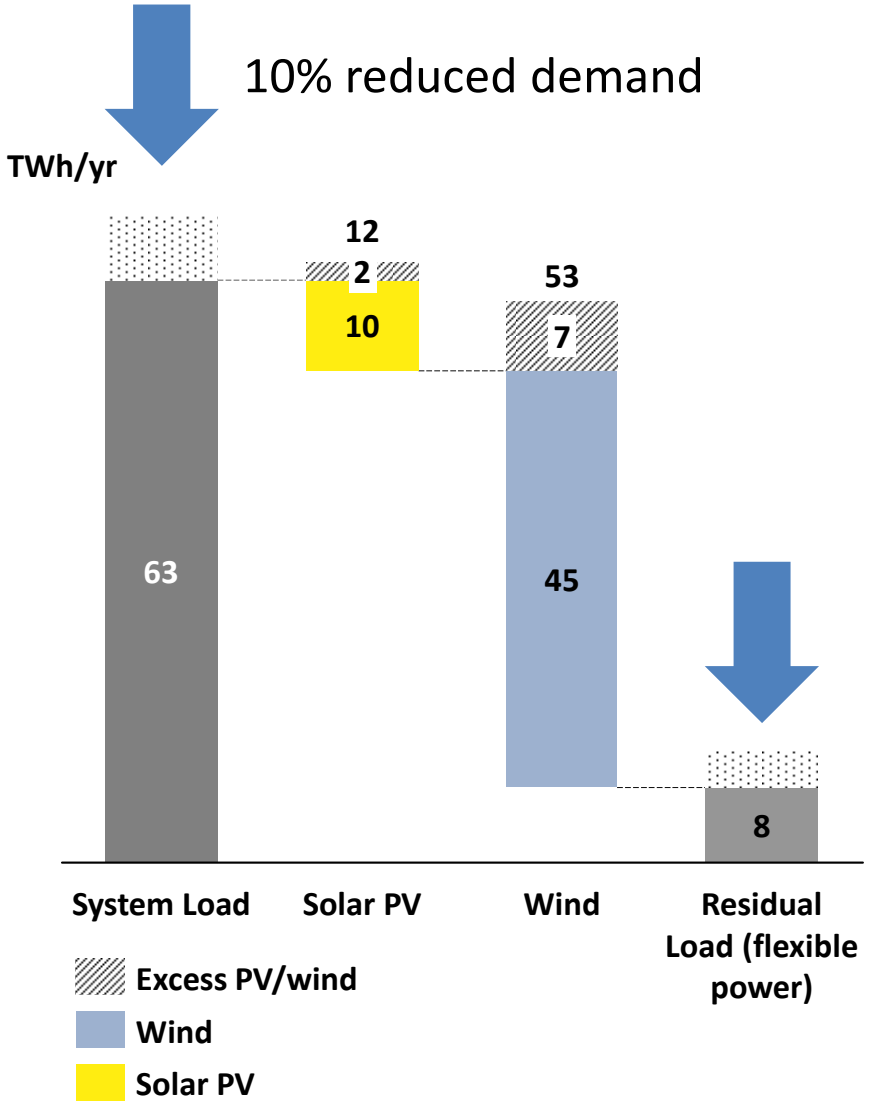
Sources: CSIR analysis

Low sensitivity to demand change (-10%): unit cost goes up by only 2%



11.5 TWh/yr * 0.87 R/kWh
+ 52.6 TWh/yr * 0.69 R/kWh
+ ~~12.1~~ 8.2 TWh/yr
* ~~2.0~~ 2.3 R/kWh

———————————————— = ~~1.01~~1.03 R/kWh

~~70.1~~ 63.1 TWh/yr

Pessimistic assumptions

- No value given to 9.1 TWh/yr of excess energy (bought and "thrown away")
- Bid Window 4 costs for PV/wind (no further cost reduction assumed)
- Very high cost for flexible power of 2.30 R/kWh assumed

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Sources: CSIR analysis

With a 10% reduction in demand, annual costs of power generation go down by R5.6 billion (mainly savings in expensive fuel)

Solar PV and Wind

Annual Solar PV tariff payments (fixed):	11.5 TWh/yr * 0.87 R/kWh =	R10.0 billion/yr
Annual wind tariff payments (fixed):	52.6 TWh/yr * 0.69 R/kWh =	R36.3 billion/yr

Flexible power generators

Annualised CAPEX and fixed O&M (fixed):		R7.3 billion/yr
Fuel cost and variable O&M (variable):	~~12.1~~ 8.2 TWh/yr * 1.40 R/kWh =	R~~17.0~~ 11.4 billion/yr

Total

Fixed cost:	(R10.0 + R36.3 + R7.3) billion/yr =	R53.6 billion/yr
Variable cost:		R~~17.0~~ 11.4 billion/yr

==========

Total **R~~70.6~~ 65.0 billion/yr**

A 10% reduction in demand reduces total costs by more than 8% → unit cost in R/kWh go up only slightly by ~2%

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Thought experiment: Build a new power system from scratch

Load profile: **As per South African system load from 2010-2012, scaled to 40 GW peak demand**

→ Annual demand: **261 TWh/yr (~10% more than today's South African demand)**

Questions:

- Technical:
  Can a blend of wind and solar PV, mixed with flexible dispatchable power to fill the gaps supply this?
- Economical: If yes, at what cost?

Assumptions/approach

1. 65 GW wind @ 0.69 R/kWh (Bid Window 4 average tariff in May-2016-Rand)
2. 25 GW solar PV @ 0.87 R/kWh (Bid Window 4 average tariff in May-2016-Rand)
3. 35 GW flexible power generator to fill the gaps @ 2.0 R/kWh (e.g. high-priced gas @ 11.3 $/MMBtu)

- 15-minute solar PV and wind data from recent CSIR study, covering the entire country
  - Check out the results: www.csir.co.za/Energy_Centre/wind_solarpv.html
- 15-minute simulation of supply structure for three entire years (2010-2012)

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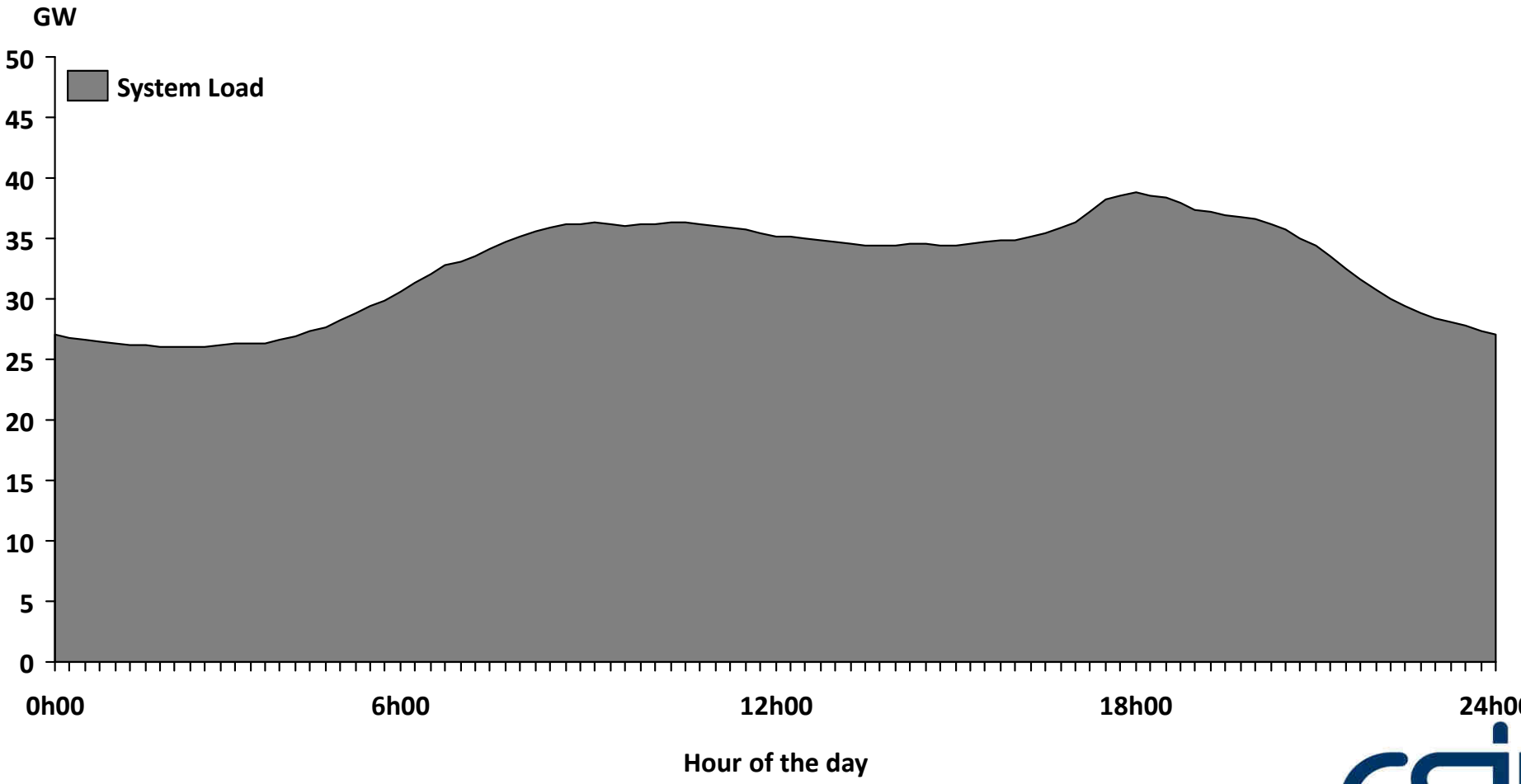
Notes: ZAR/USD = 14.0
Sources: IRP; REIPPPP outcomes; CSIR analysis

South African actual system load on 1 July 2010

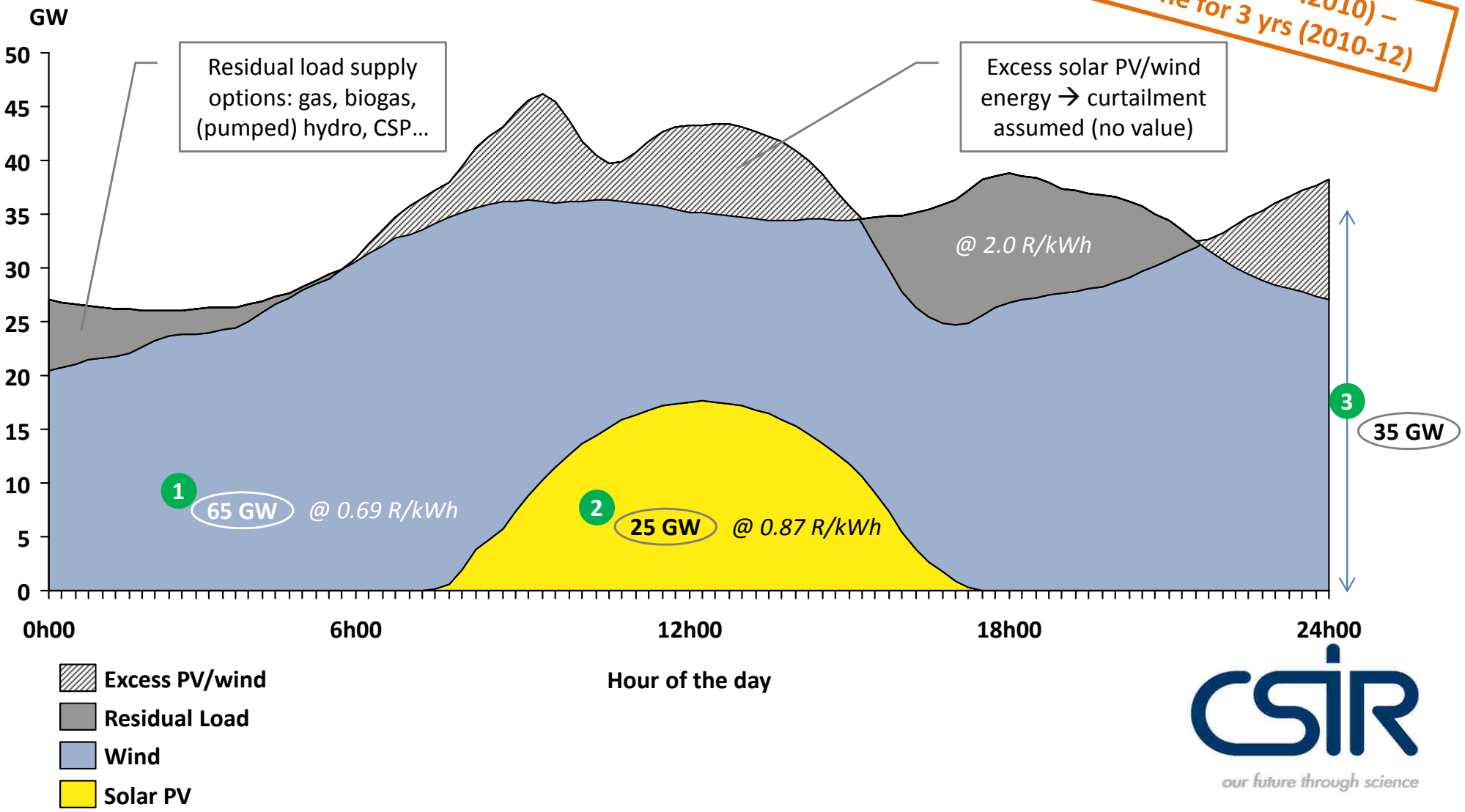


Sources: CSIR analysis

A mix of solar PV, wind and flexible power can supply this load

Actual RSA demand and simulated wind/solar PV power output for a 65 GW/25 GW fleet on 1 July 2010

One day in display (1.7.2010) – simulation done for 3 yrs (2010-12)

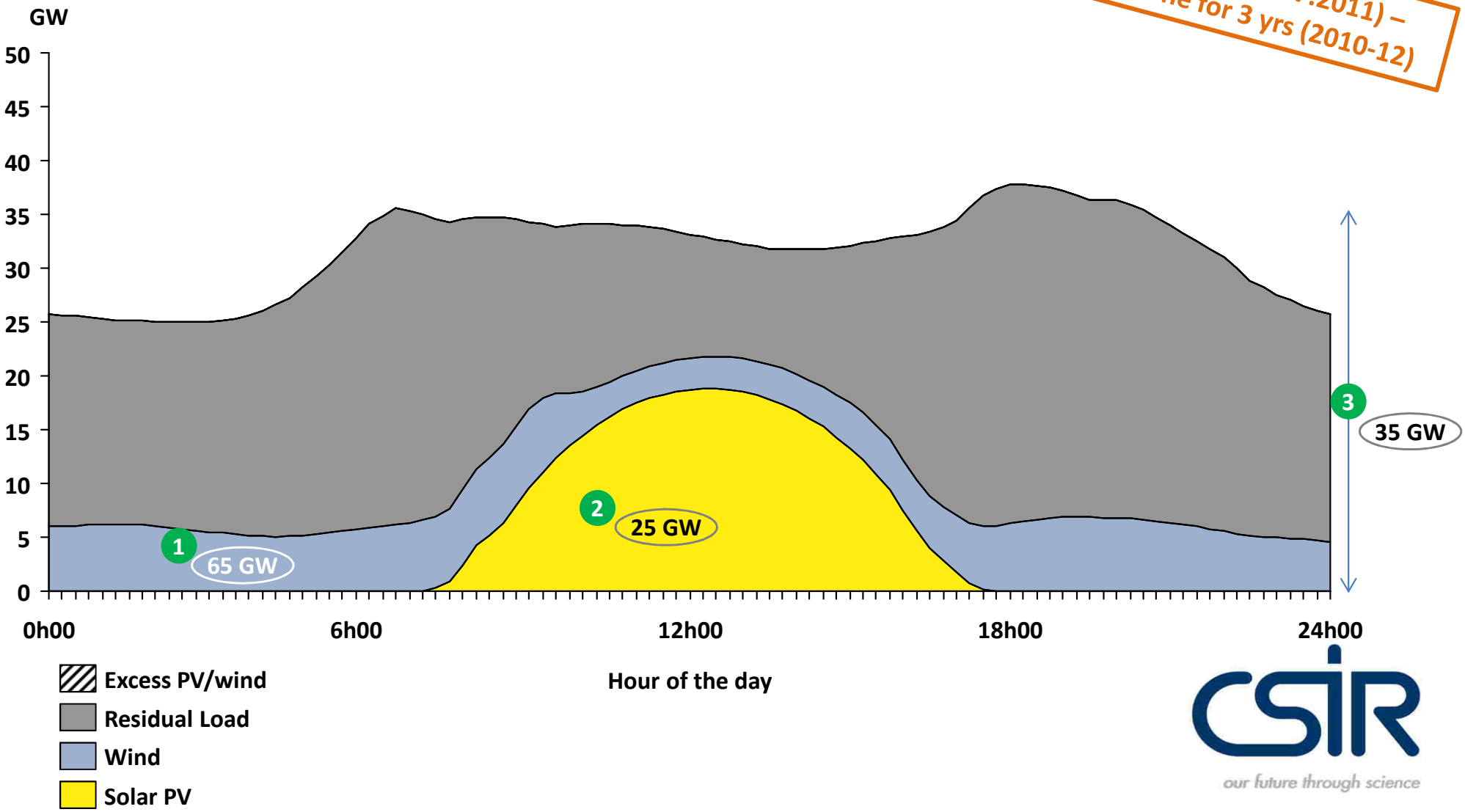


Sources: CSIR analysis

On the lowest-wind day the residual load is large

Actual RSA demand and simulated wind/solar PV power output for a 65 GW/25 GW fleet on 21 July 2011

One day in display (21.7.2011) – simulation done for 3 yrs (2010-12)

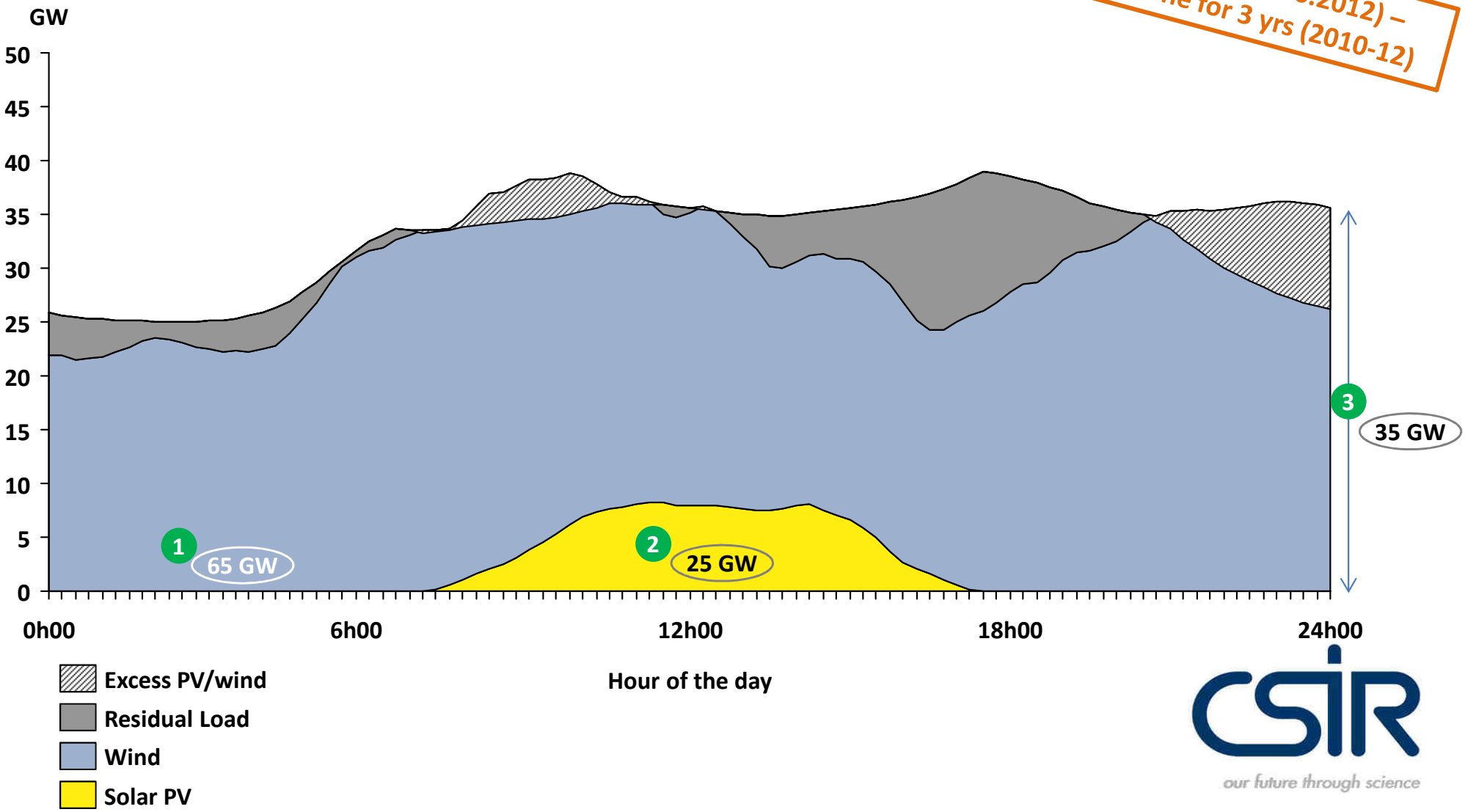


Sources: CSIR analysis

On the lowest-solar-PV day the wind fleet still contributes a lot

Actual RSA demand and simulated wind/solar PV power output for a 65 GW/25 GW fleet on 21 June 2012

One day in display (21.6.2012) – simulation done for 3 yrs (2010-12)

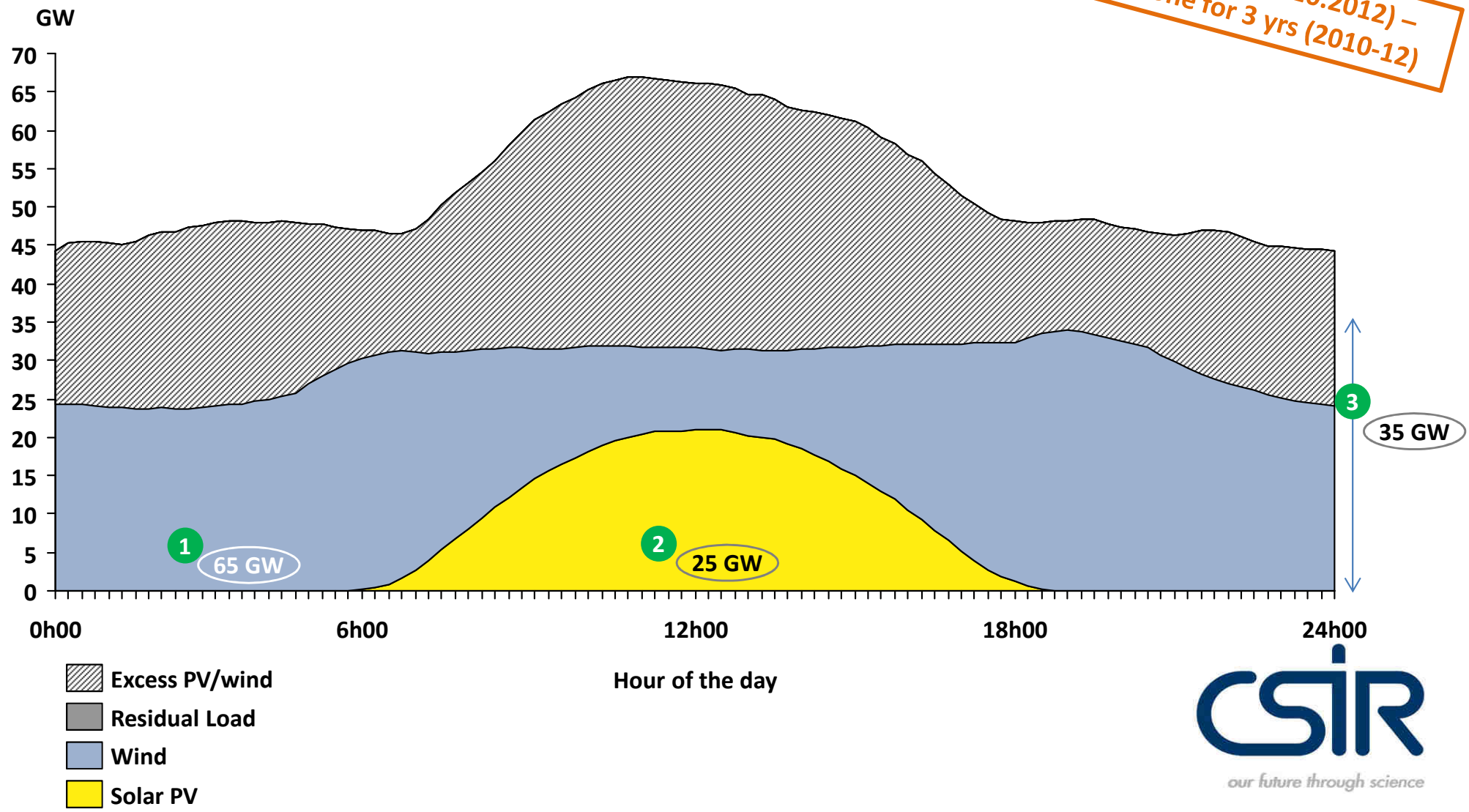


Sources: CSIR analysis

On a high-wind and solar day the amount of excess energy is large

Actual RSA demand and simulated wind/solar PV power output for a 65 GW/25 GW fleet on 30 October 2012

One day in display (30.10.2012) – simulation done for 3 yrs (2010-12)

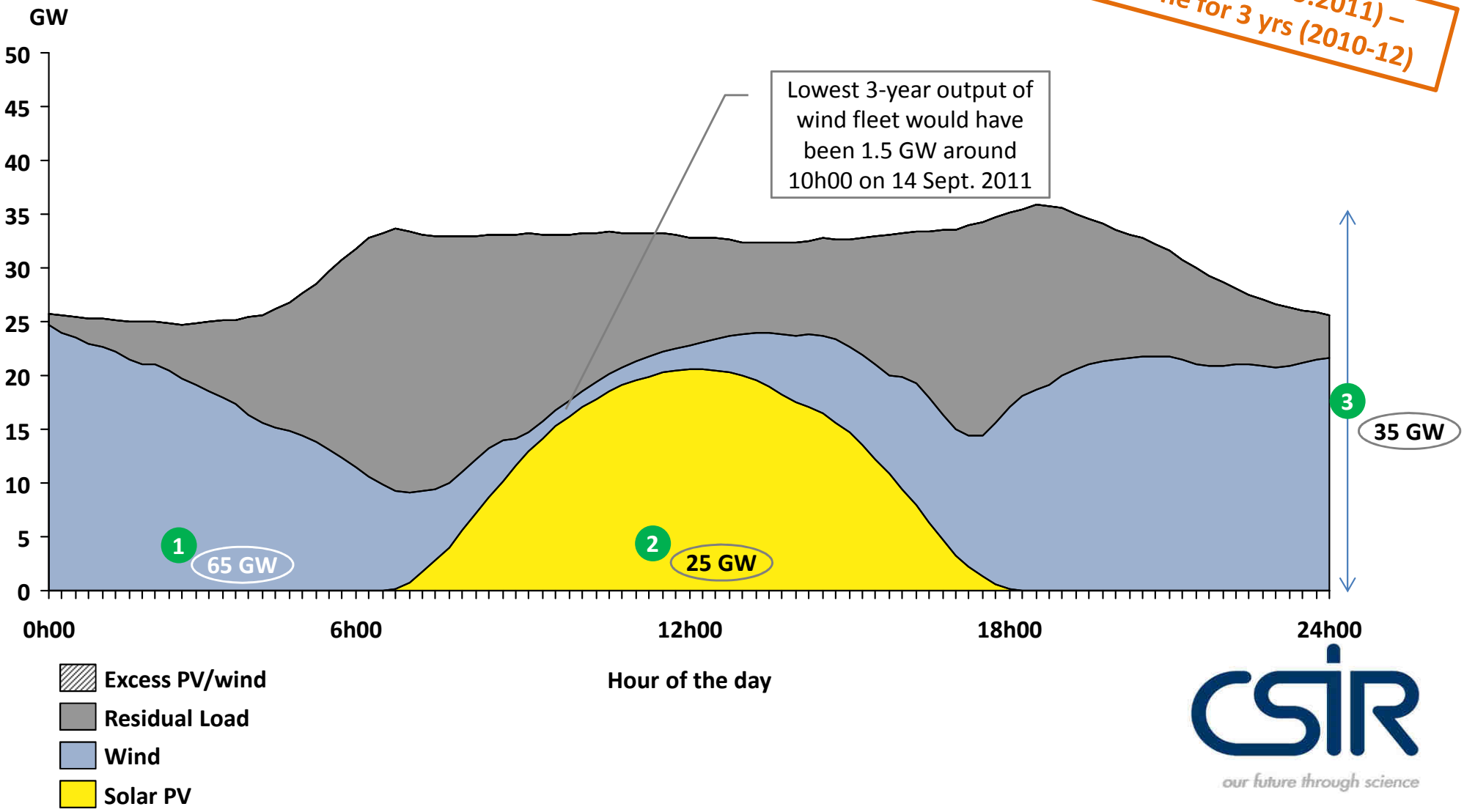


Sources: CSIR analysis

During least windy hour, output from 65 GW wind fleet is 1.5 GW

Actual RSA demand and simulated wind/solar PV power output for a 65 GW/25 GW fleet on 14 Sept. 2011

One day in display (14.9.2011) – simulation done for 3 yrs (2010-12)

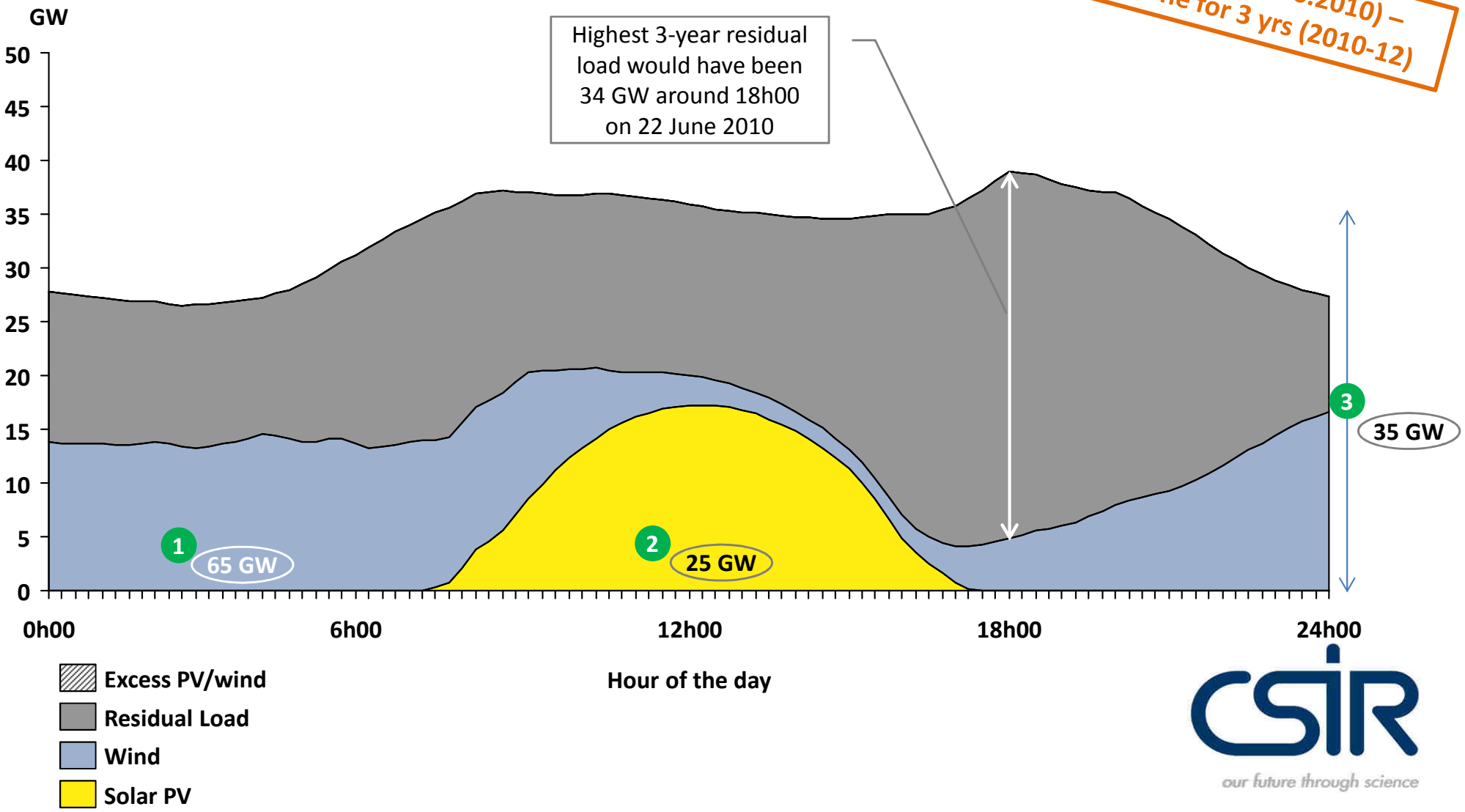


Sources: CSIR analysis

The highest residual load in the three years would have been 34 GW

Actual RSA demand and simulated wind/solar PV power output for a 65 GW/25 GW fleet on 22 June 2010

One day in display (22.6.2010) – simulation done for 3 yrs (2010-12)

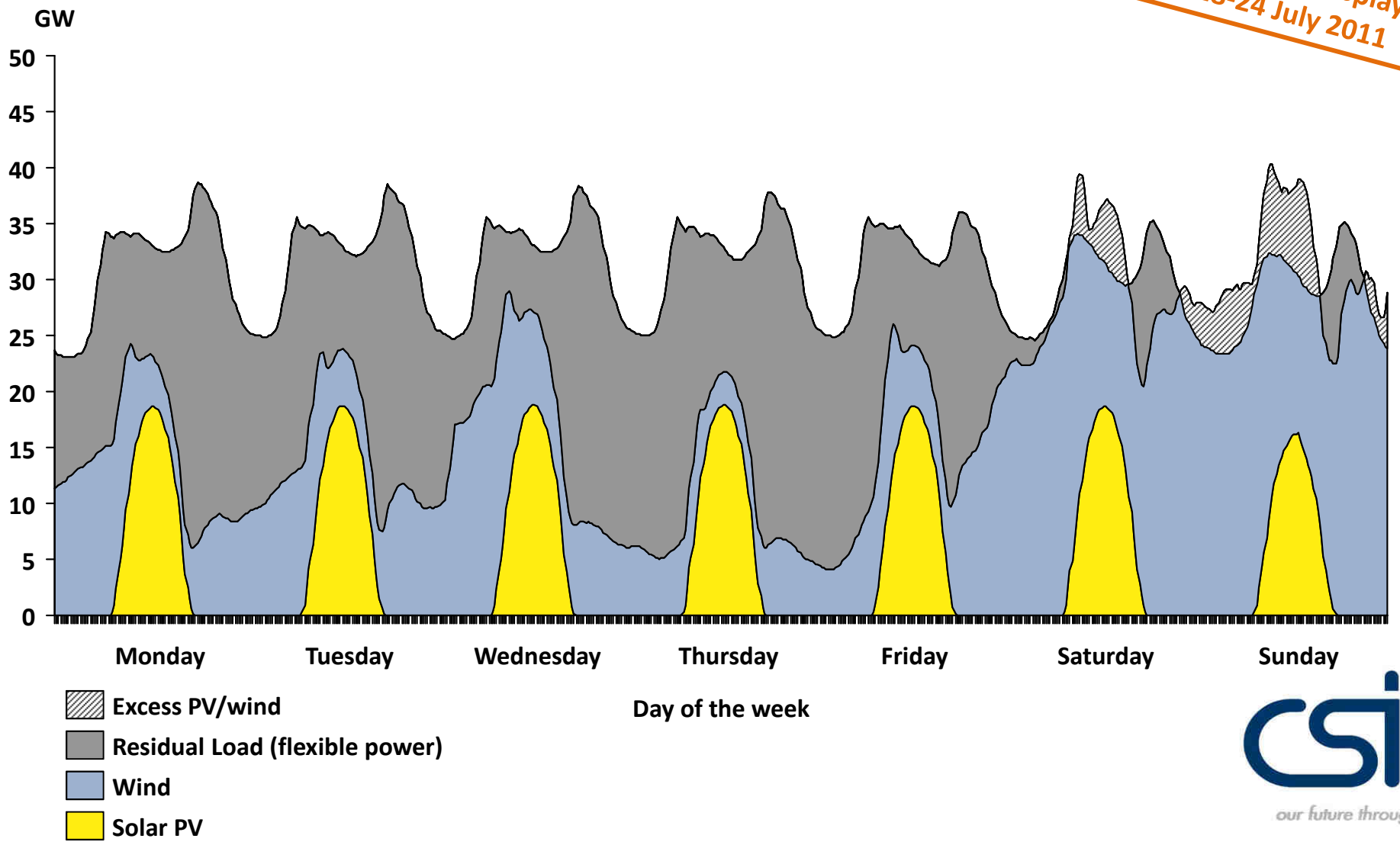


Sources: CSIR analysis

During low-wind periods, fuel for flexible generator must be stocked

Actual RSA demand and simulated 15-minute solar PV/wind power supply for the week from 18-24 July 2011

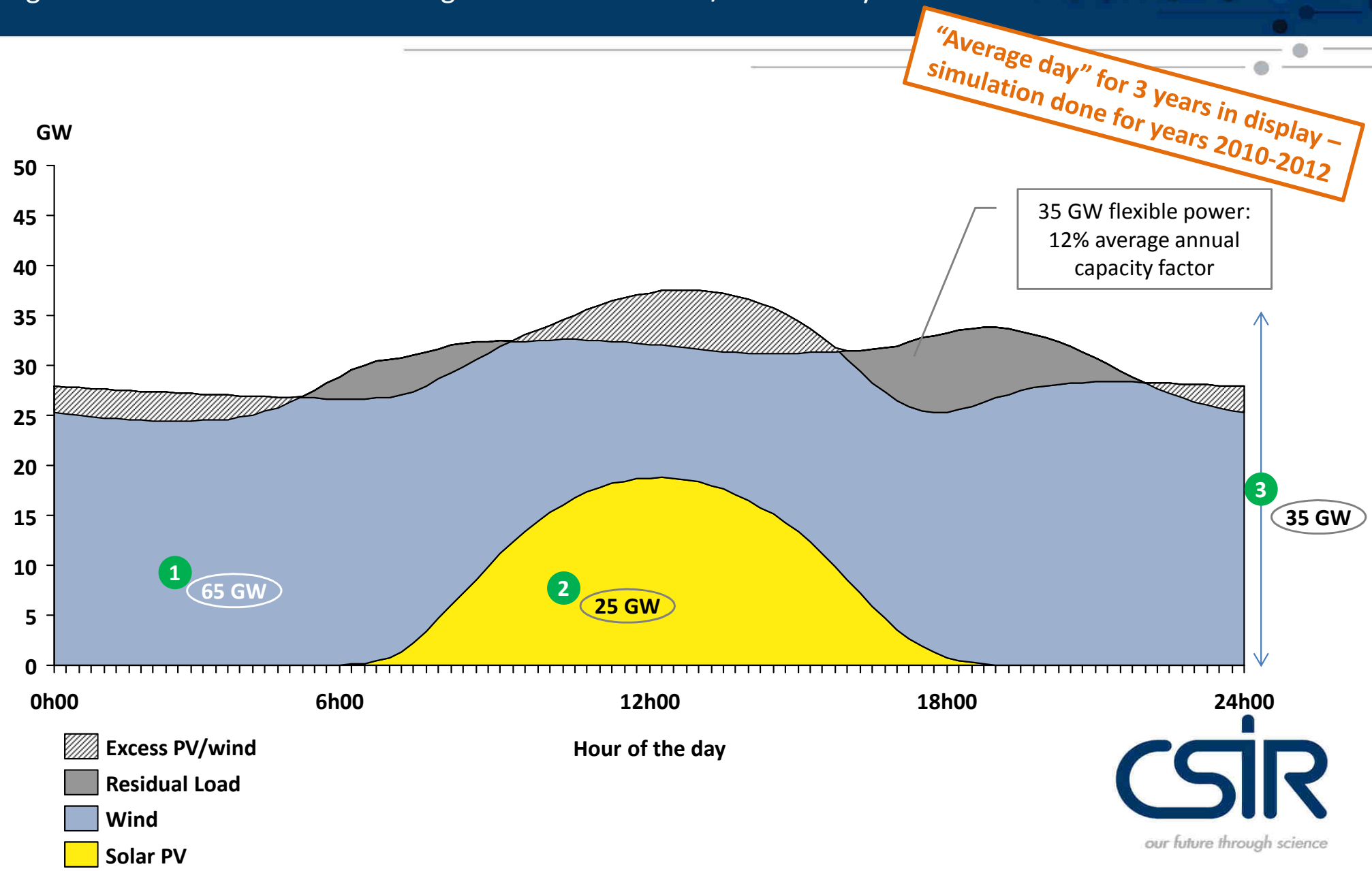
Actual week in display from 18-24 July 2011



Sources: CSIR analysis

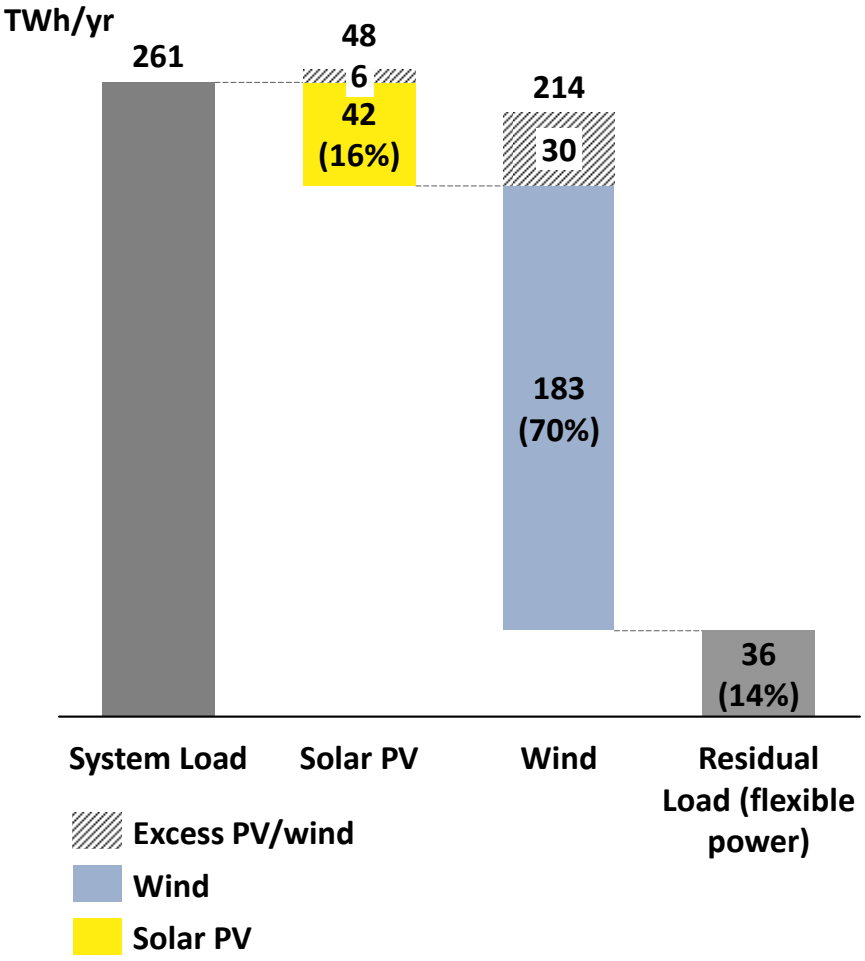
On average, solar PV and wind supply 86% of the total system load

Average actual RSA demand and average simulated solar PV/wind for 3 years from 2010-2012



Sources: CSIR analysis

Mix of solar PV, wind and expensive flexible power costs 1 R/kWh (excess thrown away) – much cheaper than mix of base- and mid-merit



New baseload coal:
0.85-1.16 R/kWh

New mid-merit coal:
1.3-1.4 R/kWh

$$\frac{48\ \text{TWh/yr} * 0.87\ \text{R/kWh} + 214\ \text{TWh/yr} * 0.69\ \text{R/kWh} + 36\ \text{TWh/yr} * 2.0\ \text{R/kWh}}{261\ \text{TWh/yr}} = 1.00\ \text{R/kWh}$$

- No value given to 36 TWh/yr of excess energy (bought and "thrown away")
- Bid Window 4 costs for PV/wind (no further cost reduction assumed)
- Very high cost for flexible power of 2.0 R/kWh assumed

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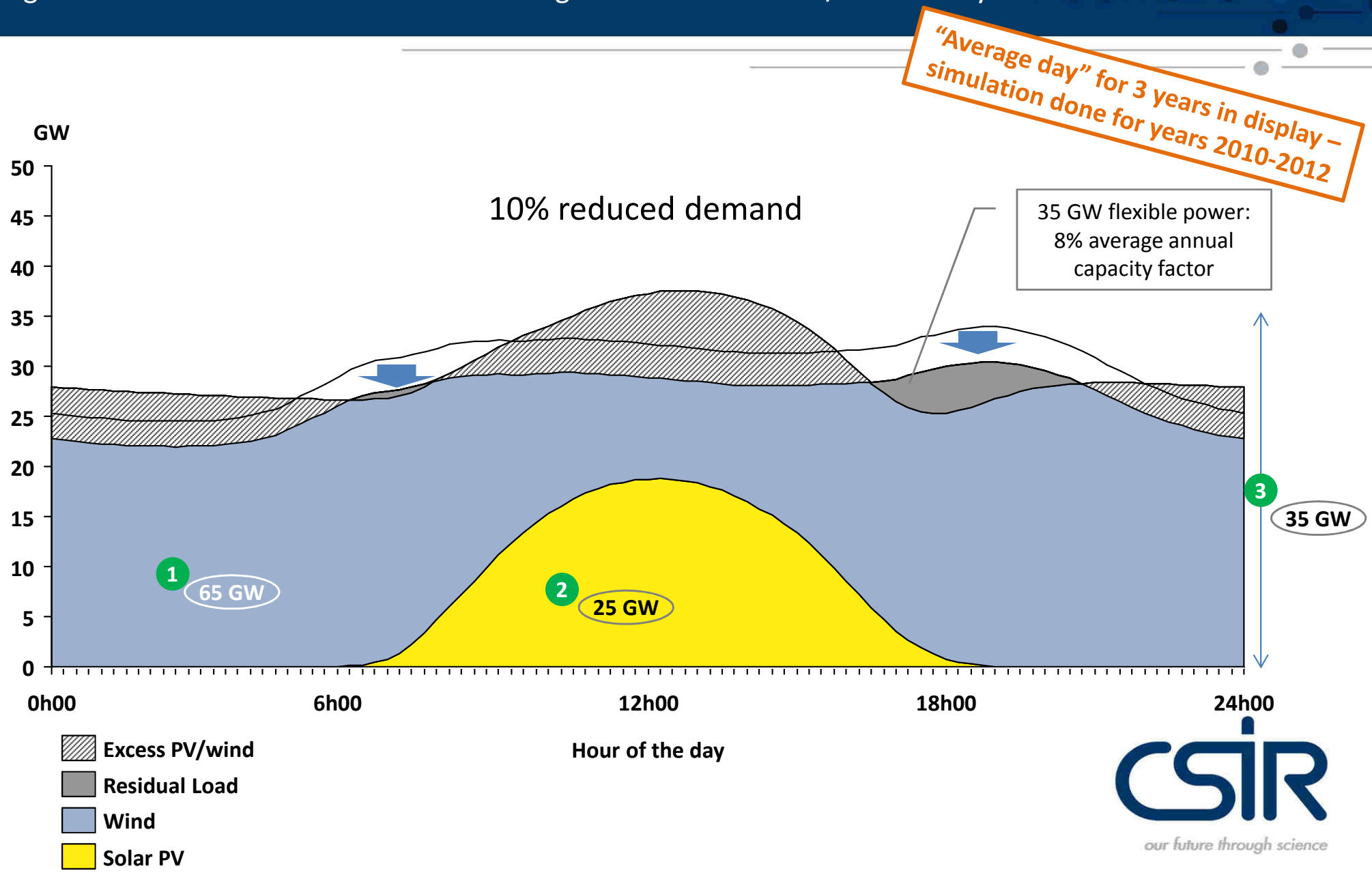
Sources: CSIR analysis

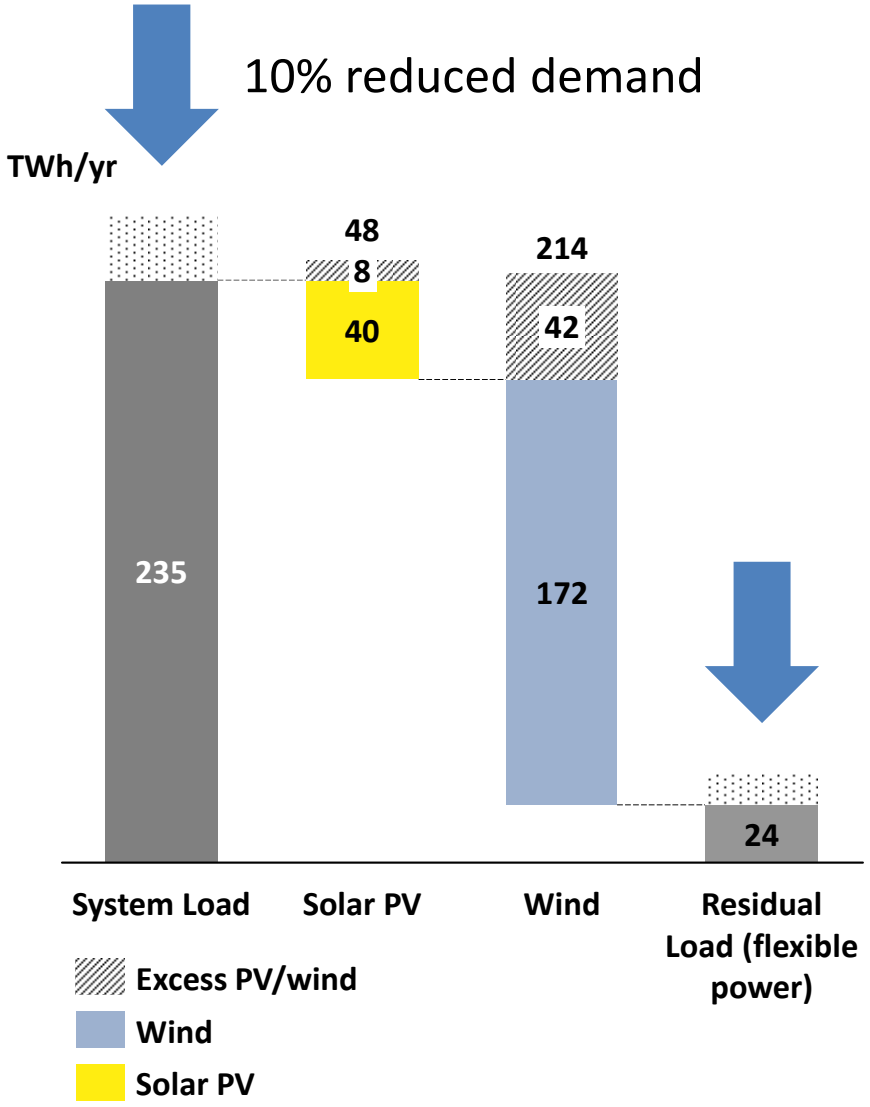
10% less load: excess energy increases, need for flexible power reduces

Average actual RSA demand less 10% and average simulated solar PV/wind for 3 years from 2010-2012



Sources: CSIR analysis

Low sensitivity to changes in demand (-10%): unit cost increases +4%



48 TWh/yr * 0.87 R/kWh
+ 214 TWh/yr * 0.69 R/kWh
+ ~~36~~ 24 TWh/yr
* ~~2.0~~ 2.3 R/kWh

——————————————————— = ~~1.00~~1.04 R/kWh

~~261~~ 235 TWh/yr

- No value given to 50 TWh/yr of excess energy (bought and "thrown away")
- Bid Window 4 costs for PV/wind (no further cost reduction assumed)
- Very high cost for flexible power of 2.3 R/kWh assumed

Sources: CSIR analysis

What we have learned from having high-fidelity wind data available

Before high-fidelity data collection …	… and after
Wind resource in South Africa is not good	Wind resource in South Africa is on par with solar
There is not enough space in South Africa to supply the country with wind power	>80% of the country's land mass has enough wind potential to achieve 30% capacity factor or more
Wind power has very high short-term fluctuations	On portfolio level, 15-minute gradients are very low
Wind power has no value because it is not always available	On average, wind power in South Africa is available 24/7 with higher output in evenings and at night
	In a mix with cheap solar PV and expensive flexible power it is cheaper than dispatchable alternatives

… analyses to be continued

Re a leboha

Ha Khensa

Enkosi

Siyathokoza

Thank you!

Re a leboga

Ro livhuha

Dankie

Siyabonga