

Energy Storage & Future Grids

PowerFactory Users' Conference

Friday, 6 September 2013, Sydney Harbour Marriott Hotel, Sydney

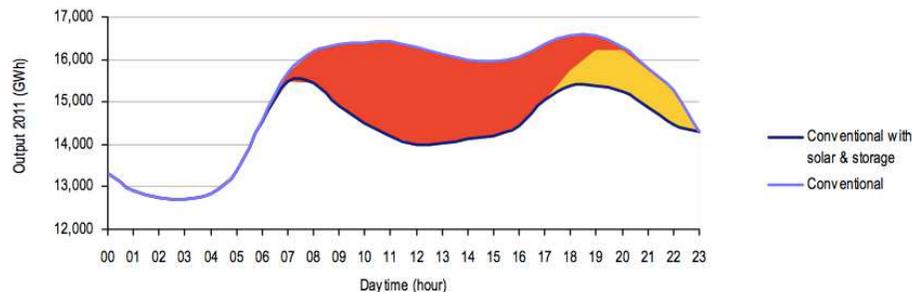
Dr Gregor Verbic
School of Electrical and Information Engineering



- › Overview of the power system as we know it
- › Drivers for evolution of power systems
- › How will the future grids look like
- › Role of storage in future grids
- › Alternative storage options

- › No so long ago, this presentation would have been considered highly speculative but today it seems the changes are here to stay.
- › PV penetration keeps growing at an incredible rate and the proliferation of solar seems to be unstoppable.
- › Germans have introduced financial incentives for battery storage.
- › Vector's (NZ's utility) home solar electricity system.
- › Etc...

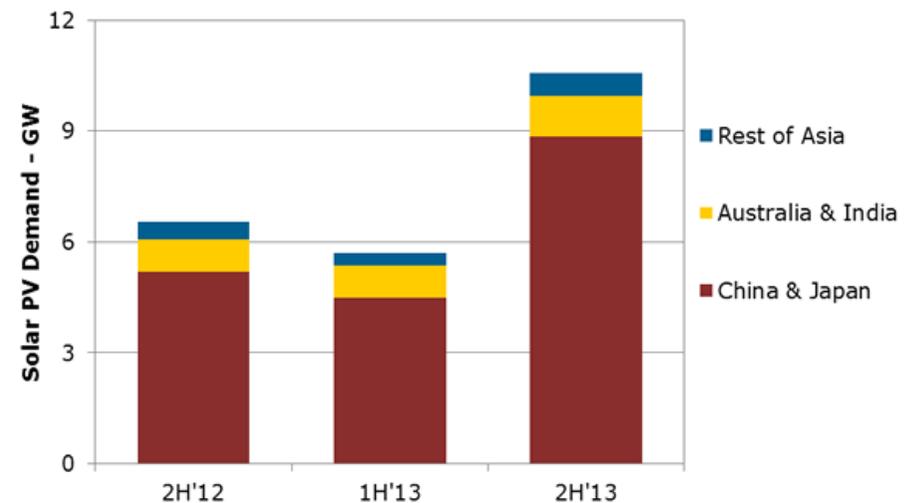
Chart 37: Impact of unsubsidised solar on thermal generation even larger in combination with battery systems (Germany, 2020E)



Source: UBS estimates

Note: The red area is the reduction in conventional output due to solar generation; the yellow area represents the peak shaving effect of solar battery systems.

reneweconomy.com.au

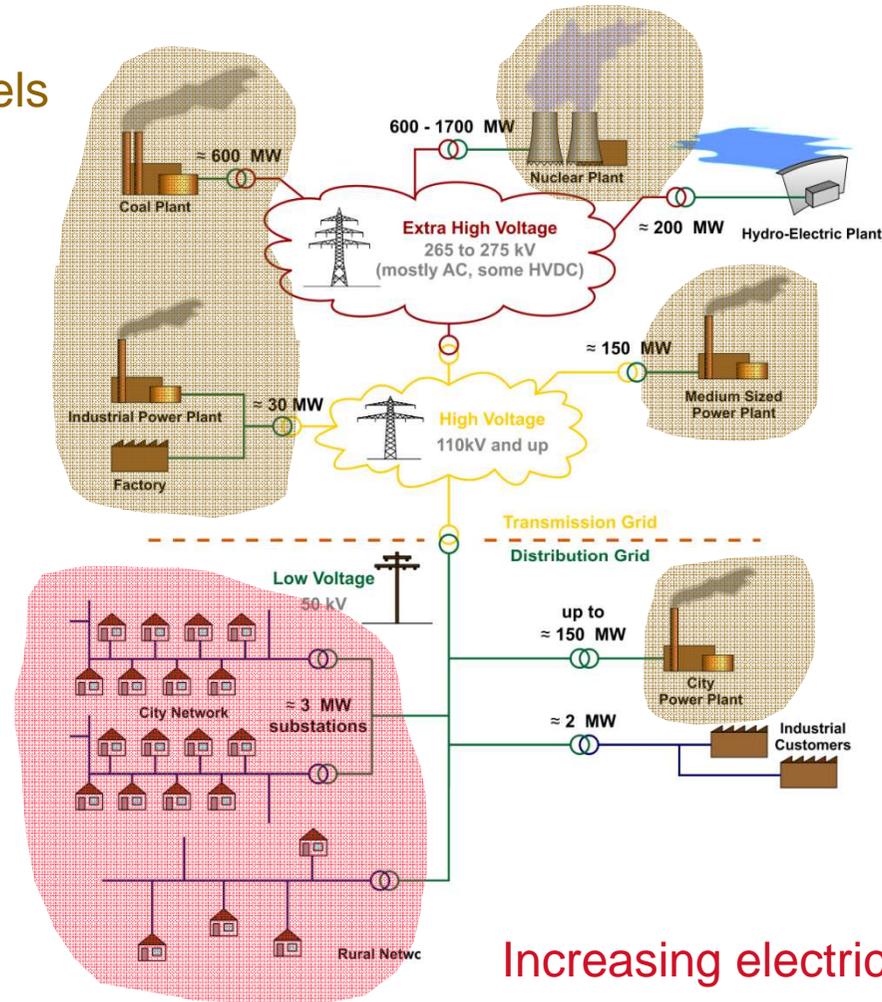


The evolution of power systems – the drivers



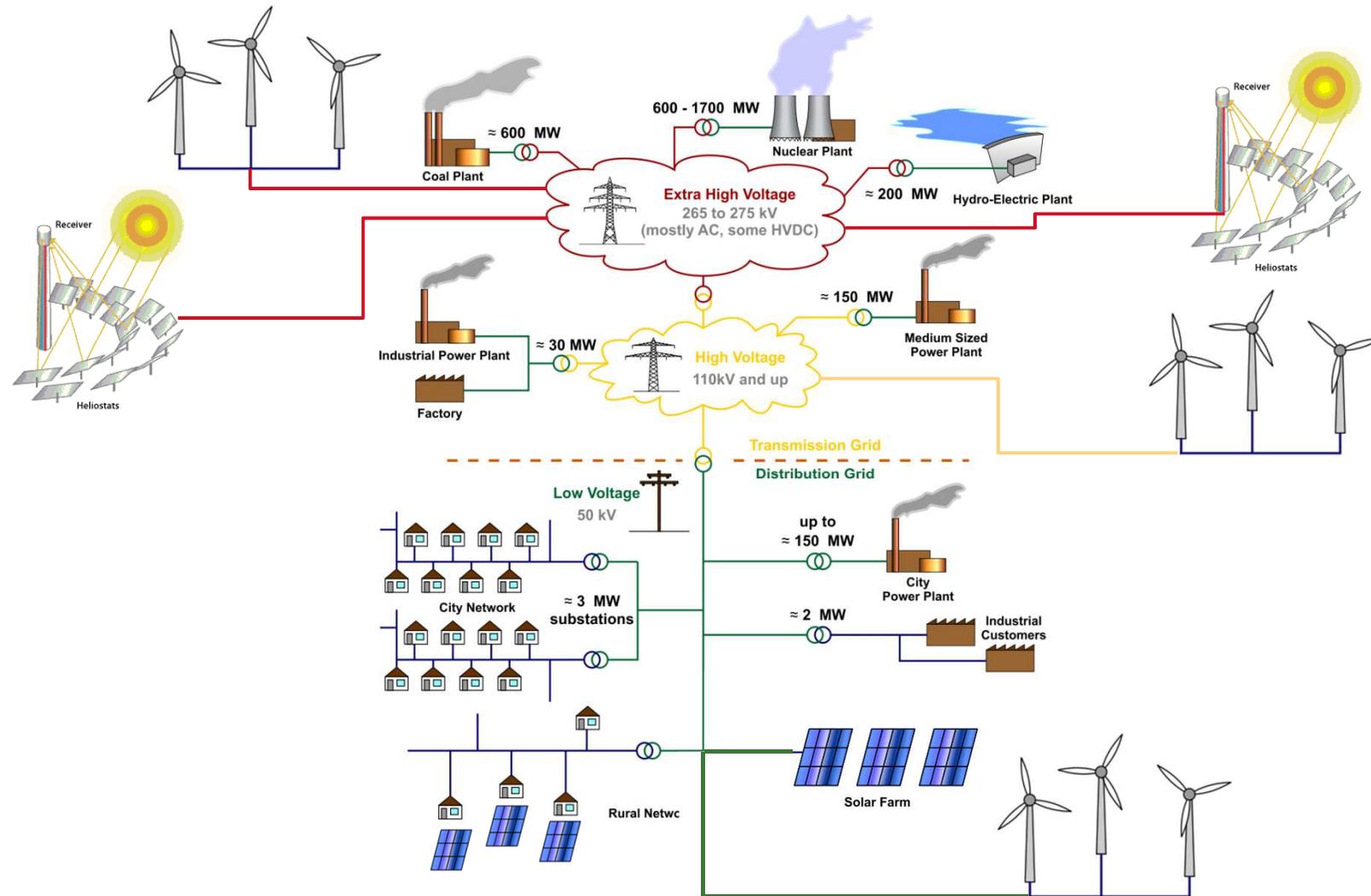
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Dwindling fossil fuels
CO₂ emissions



Increasing electricity prices

Power system as we know it



Source: Wikipedia

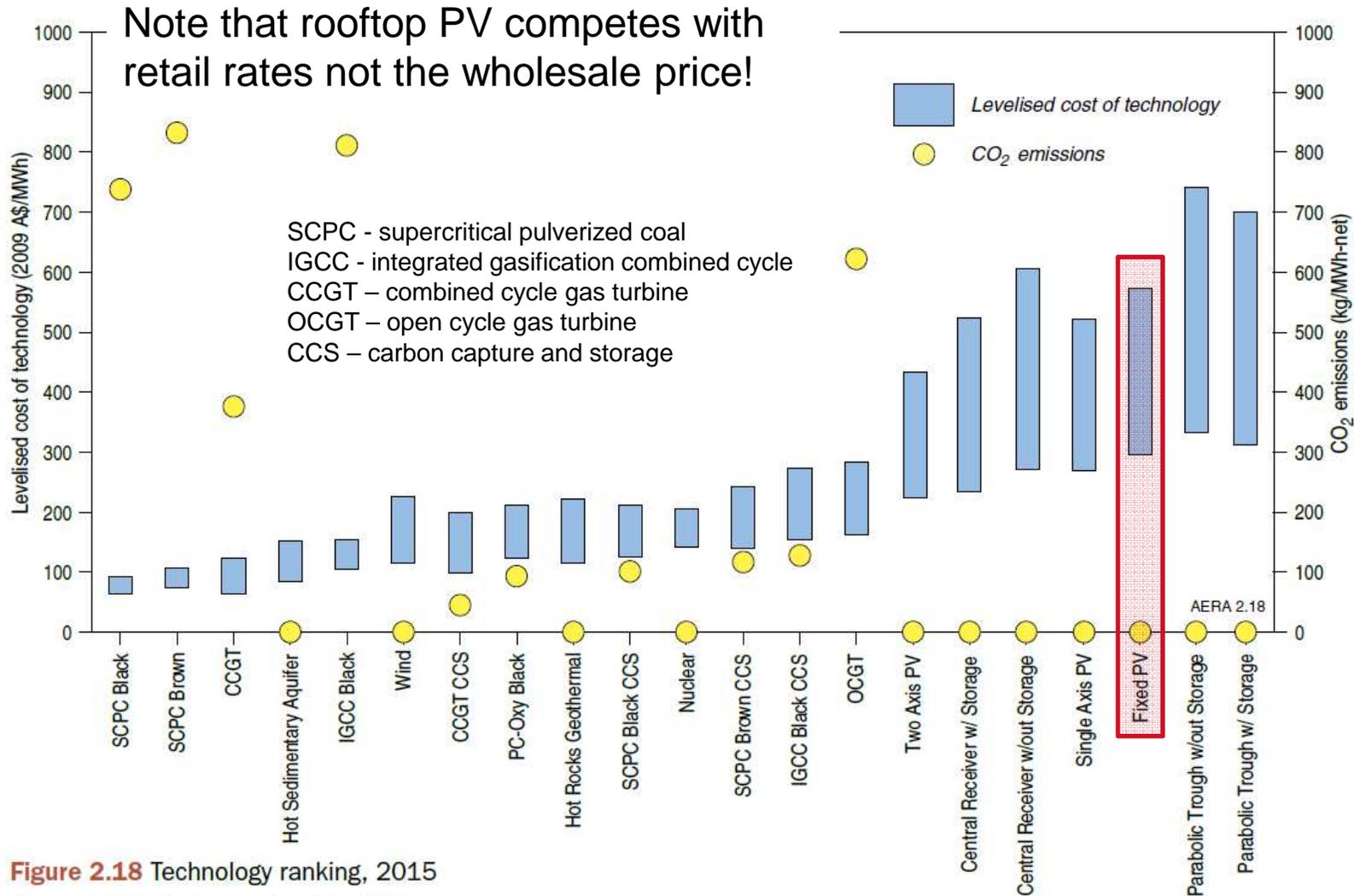
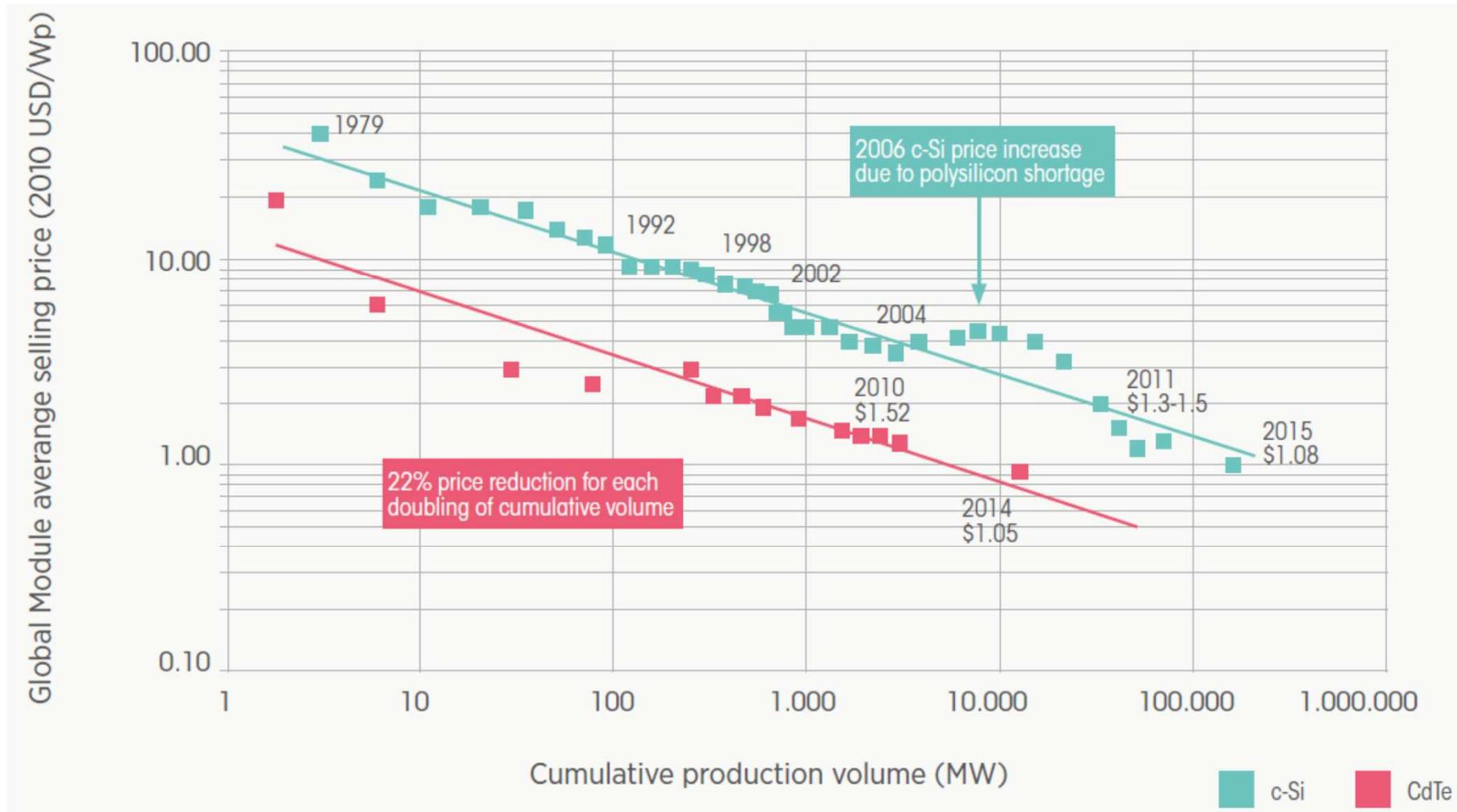


Figure 2.18 Technology ranking, 2015

Source: EPRI technology status data, 2010

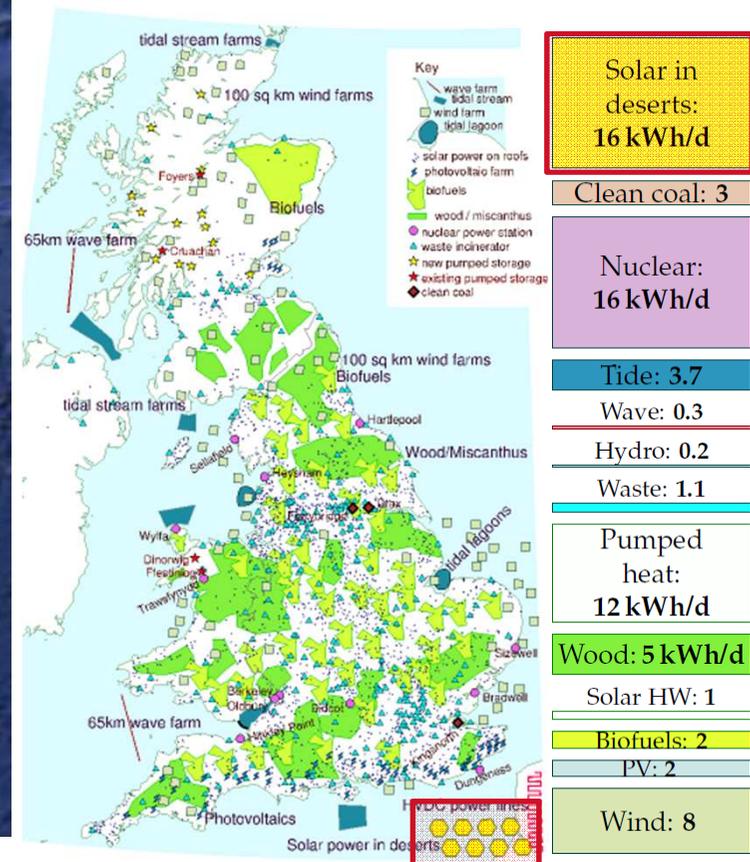
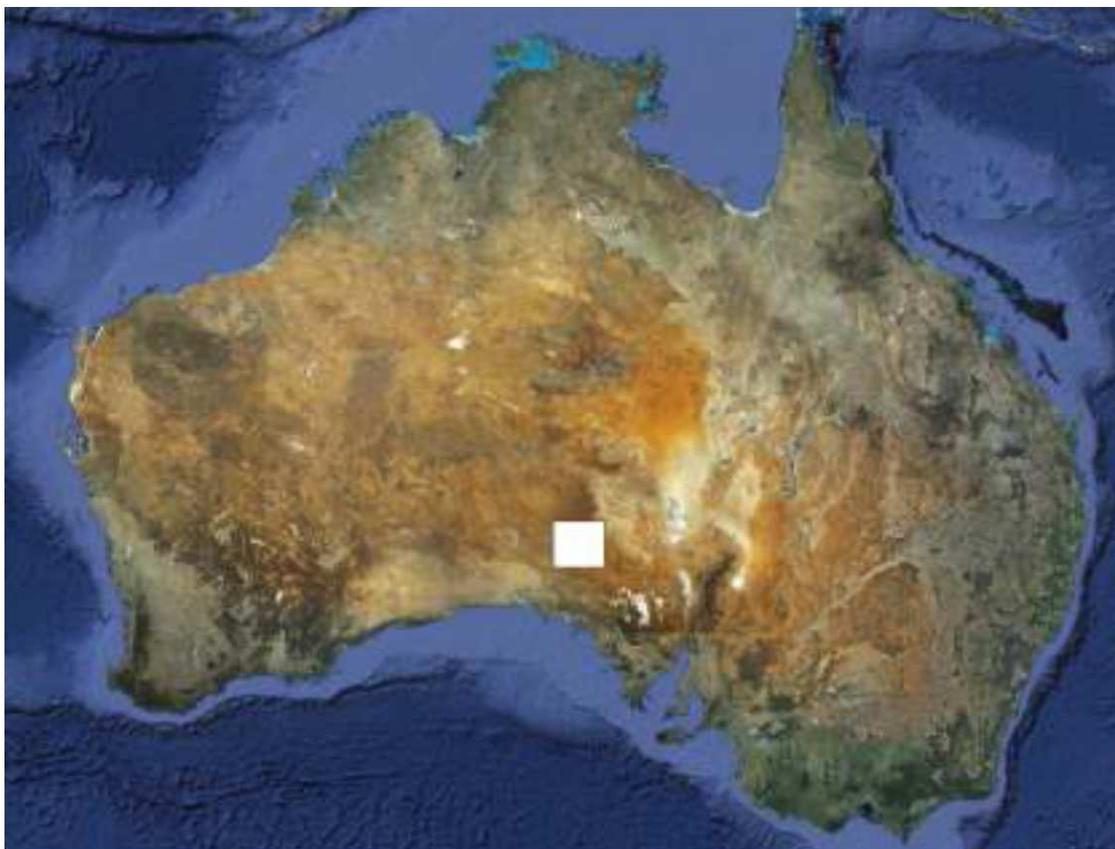
The global PV module price learning curve



The International Renewable Energy Agency (IRENA), 2012, Renewable Energy Cost Analysis - Solar Photovoltaics.

Going 100% renewable

- › To provide all of Australia's gross energy from solar power 200 x 200 km² square would be sufficient (using conservative 4.5 W/m²).

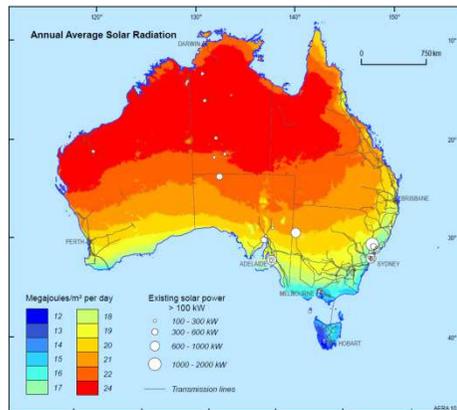
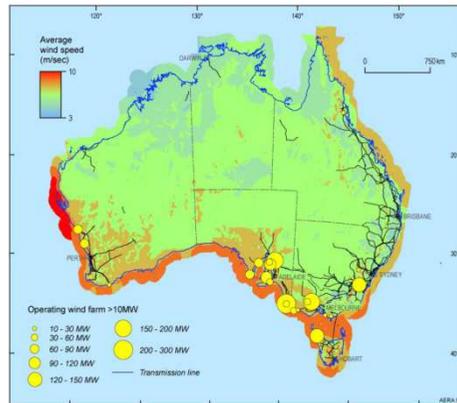


Sources: Peter Seligman, Australian Sustainable Energy – by the numbers

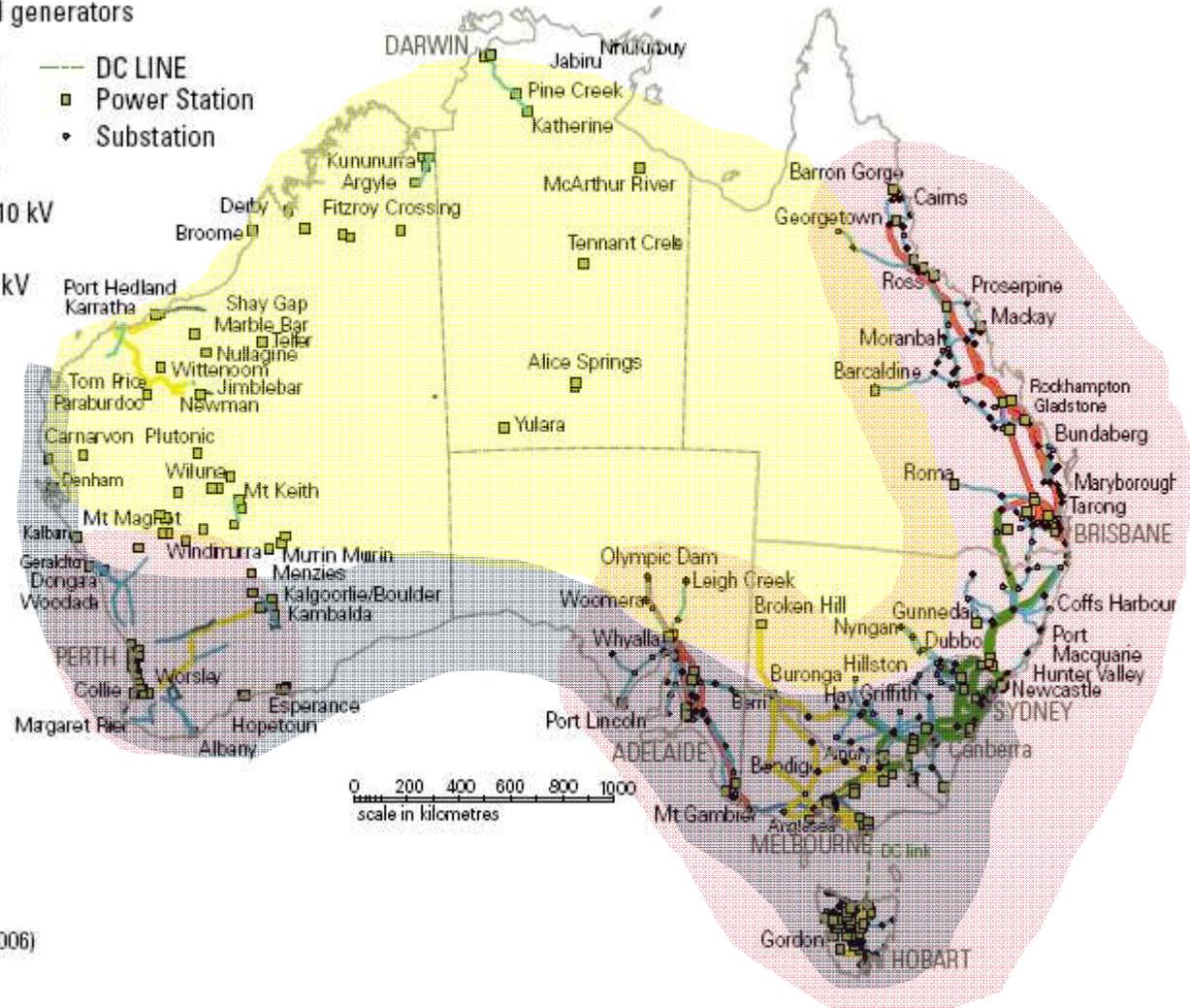
David MacKay, 2009, Sustainable Energy - without the hot air. www.withouthotair.com

Australian transmission network

Transmission lines and generators



- 500 kV
- 330 kV
- 275 kV
- 220 kV
- 132 / 110 kV
- 66 kV
- 33 / 22 kV
- DC LINE
- Power Station
- Substation

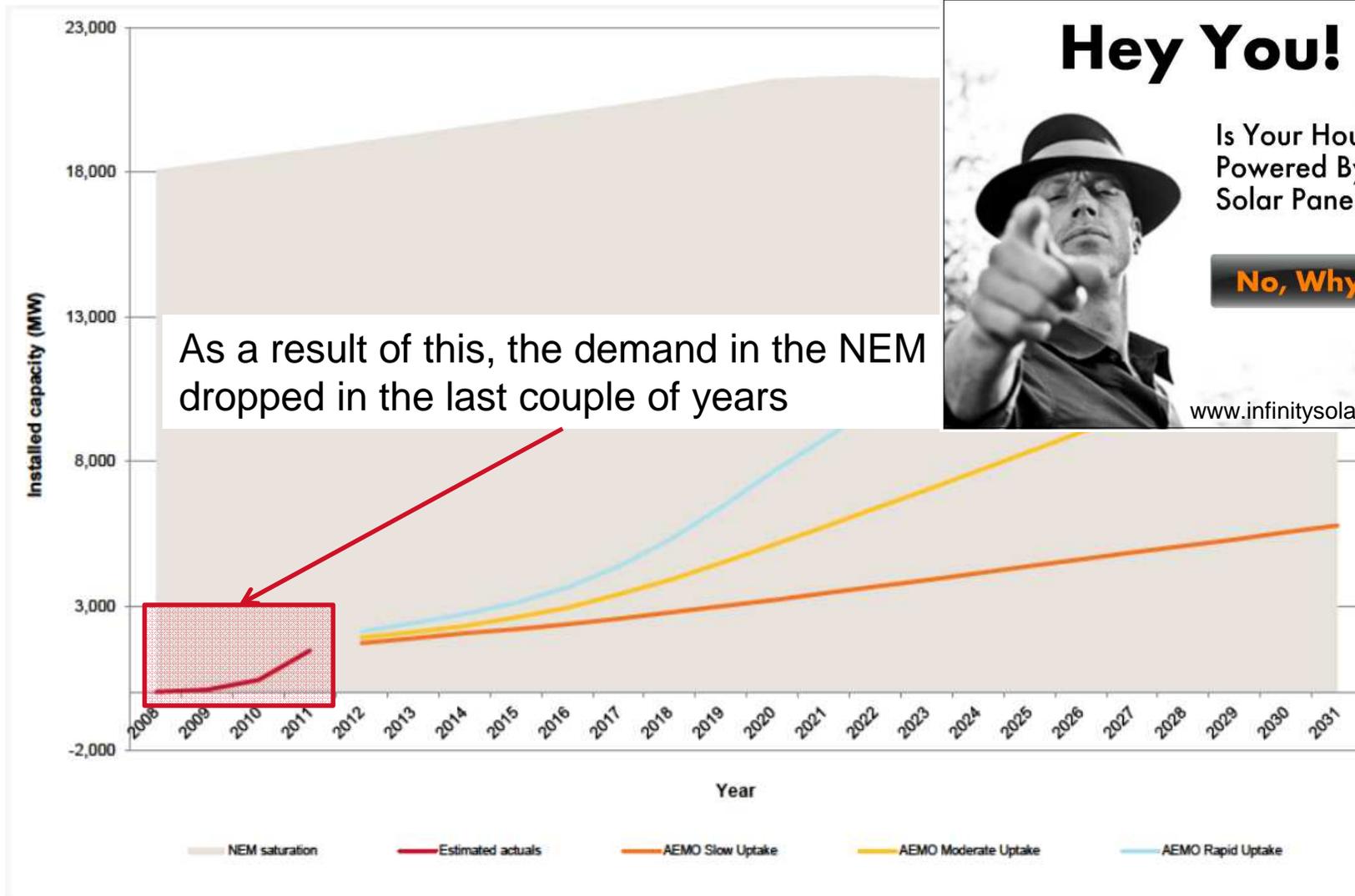


Locations are indicative only.

Sources: NEMMCO, ESAA (2006)

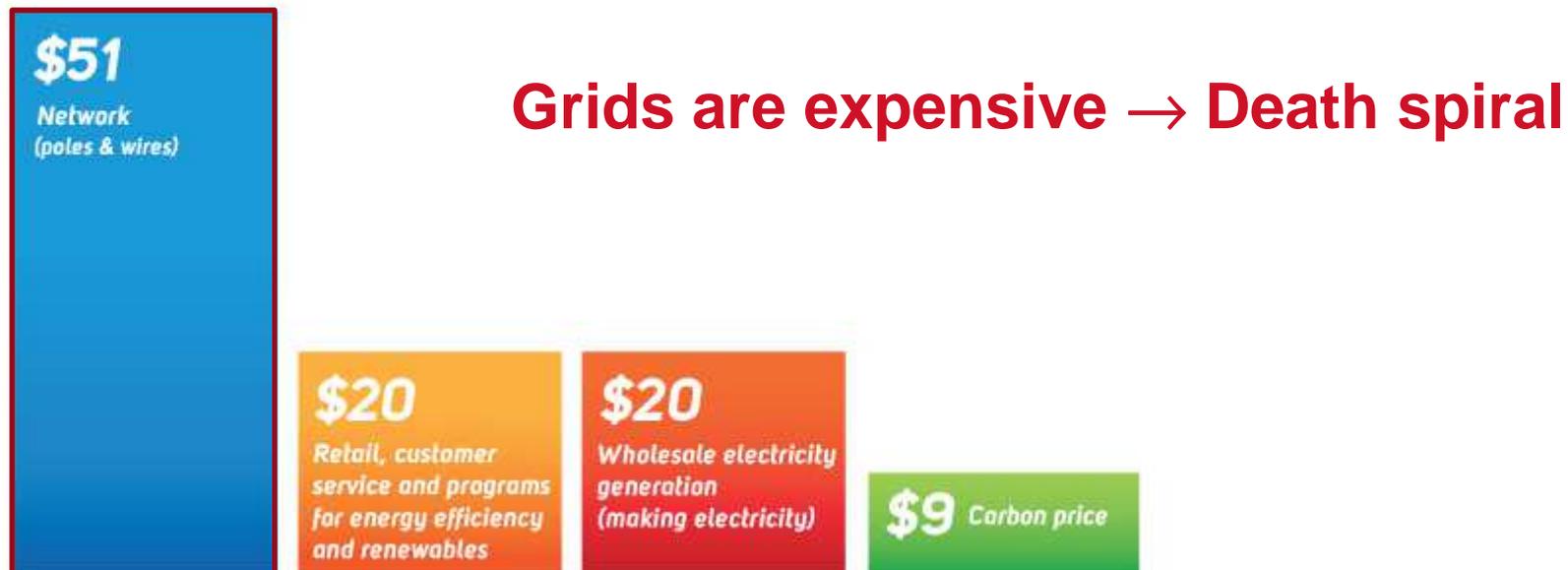
Source: ABARES - Australian Energy Resource Assessment

Rooftop PV installed capacity forecast for the NEM



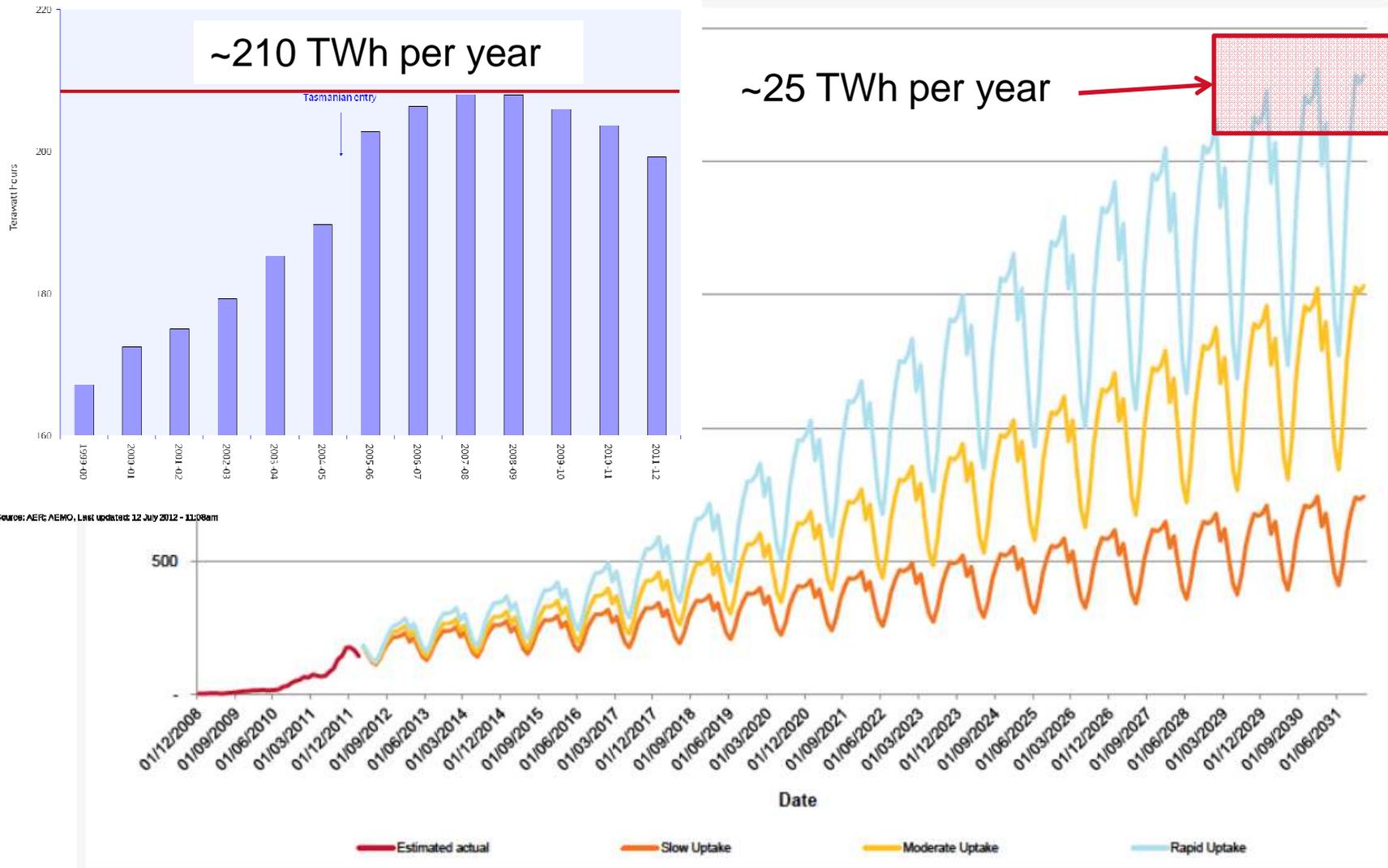
The effect of PV on residential electricity prices

- › The DNOs and TNOs recover the costs through network (distribution and transmission) charges.
- › As a result of the dropping consumption, the network charges will need to go up for the DNOs and TNOs to recover the costs, which will effectively drive the prices further up.



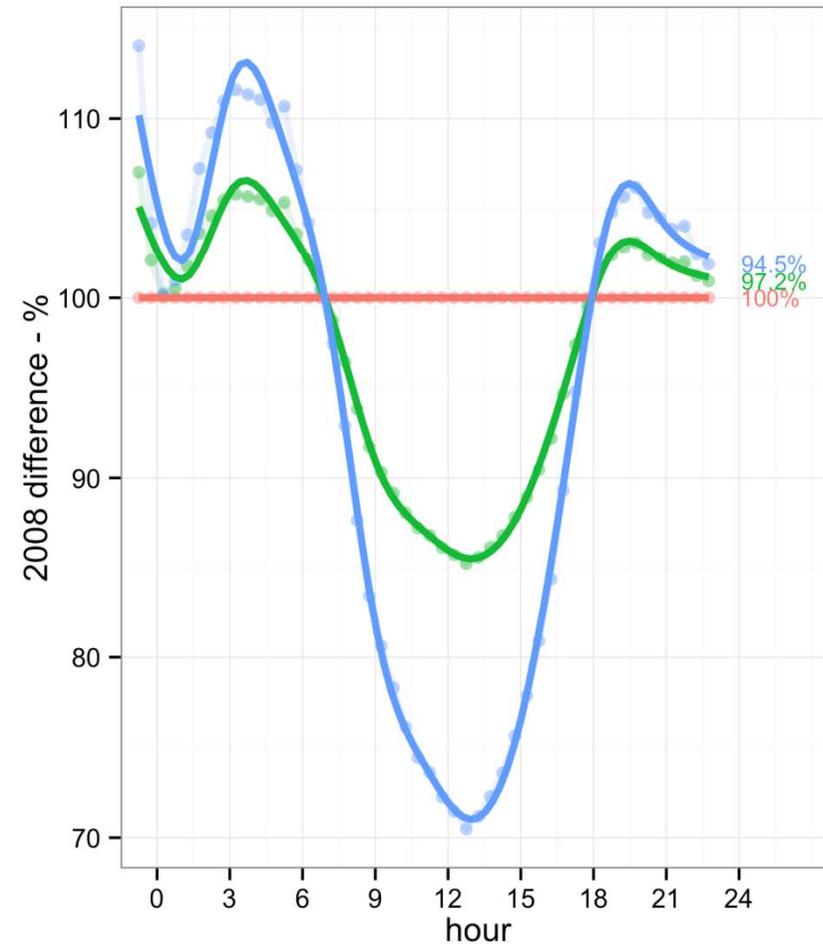
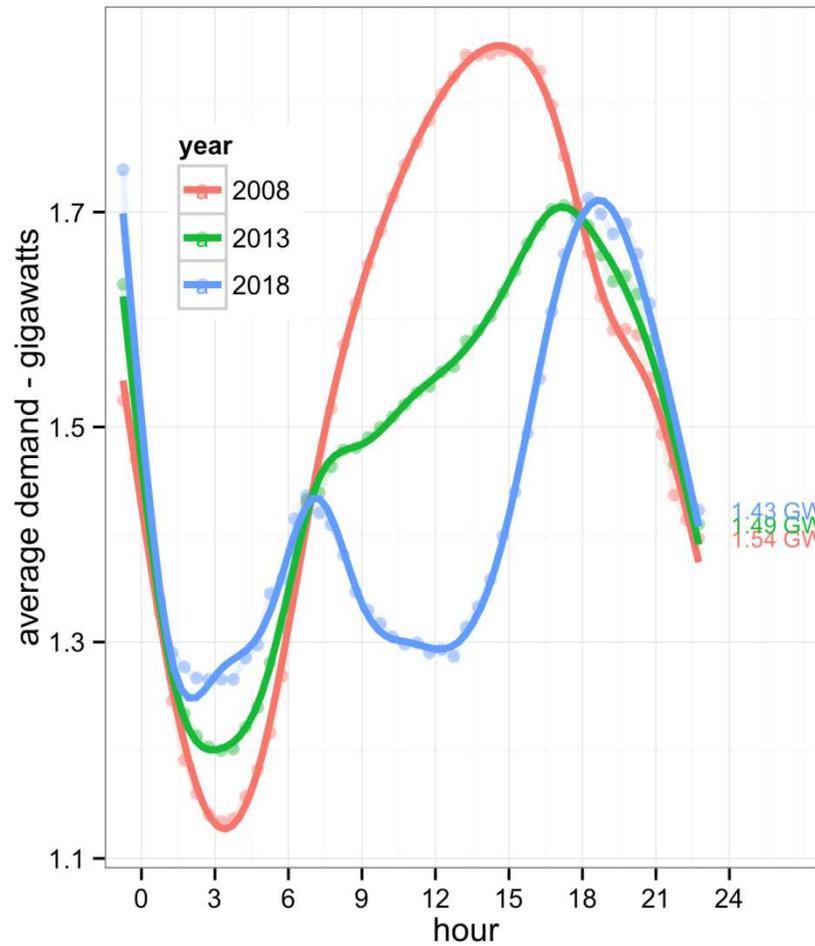
Source: www.cleanenergyfuture.gov.au/

Rooftop PV energy forecast for the NEM



The effect of PV in South Australia

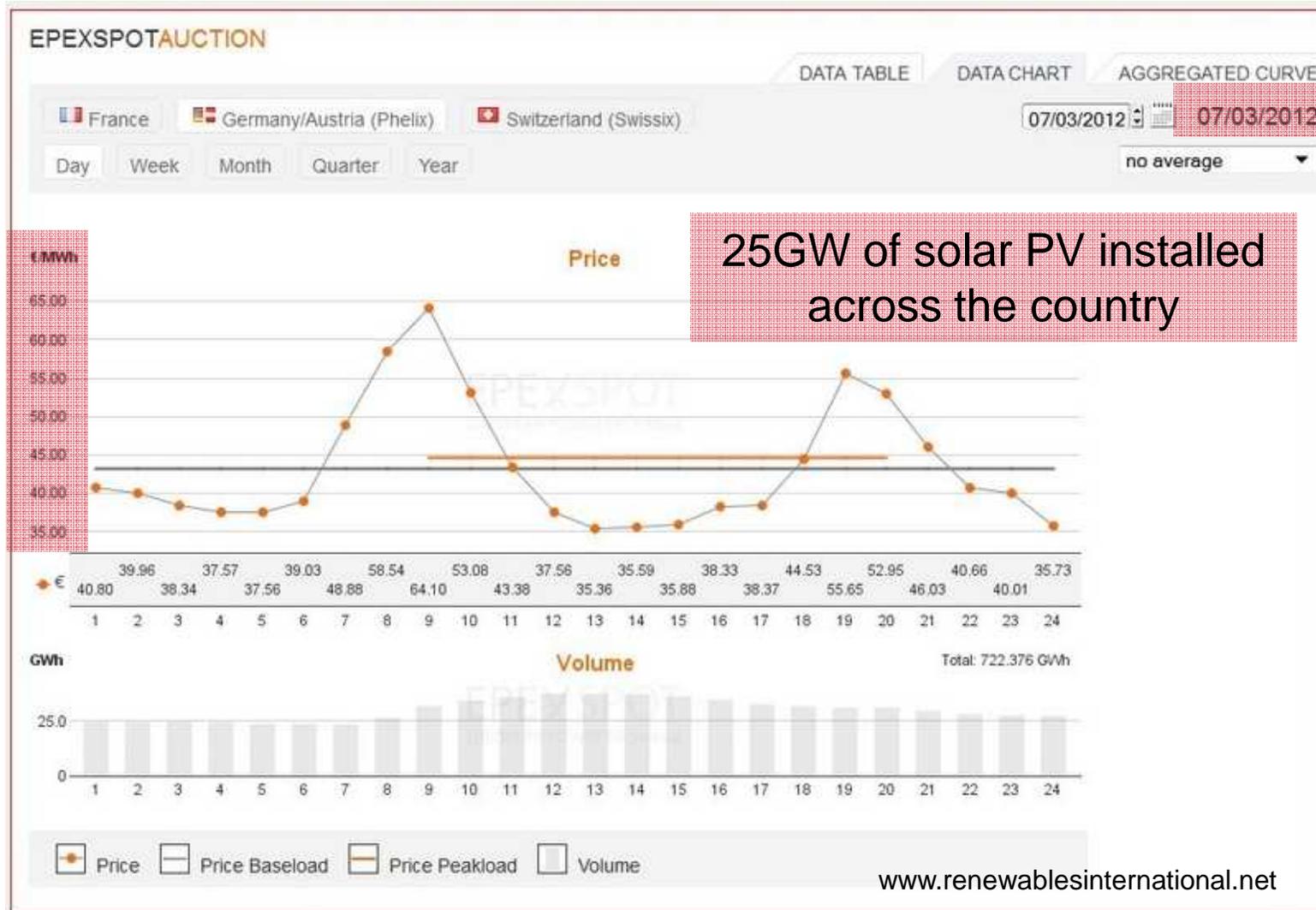
SA : average demand for summer months December-January



What does this mean for the incumbents?



What does this mean for the incumbents?



Germany introduces incentives for battery storage

- › Energy storage incentives launched 1 May 2013.
- › Purchase of new battery storage for solar power systems subsidized up to €660 per kilowatt of solar panels; up to a maximum of 30kW.
- › The subsidy is equal to 30% of current battery costs.

Figure 20. Generation profile before storage

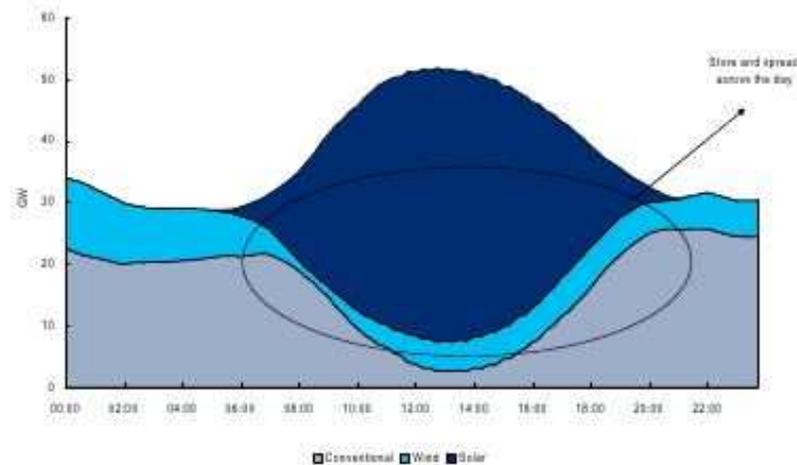
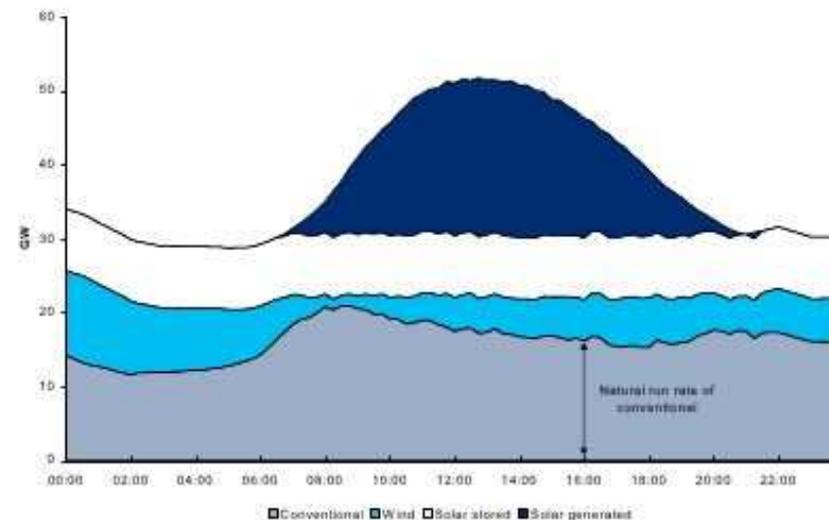


Figure 21. Generation profile once storage is installed



› Policy uncertainty

- High carbon price → large penetration of intermittent renewables (mostly wind and CSP)
- No/low carbon price → fossil fuel based generation dominant in the foreseeable future
- **BUT:** the proliferation of solar seems unstoppable so business models of the incumbent utilities and market rules (capacity charges?) will need to adapt

› Price uncertainty

- Residential electricity prices will go up significantly → accelerated uptake of residential distributed generation (**smart homes** will become viable)

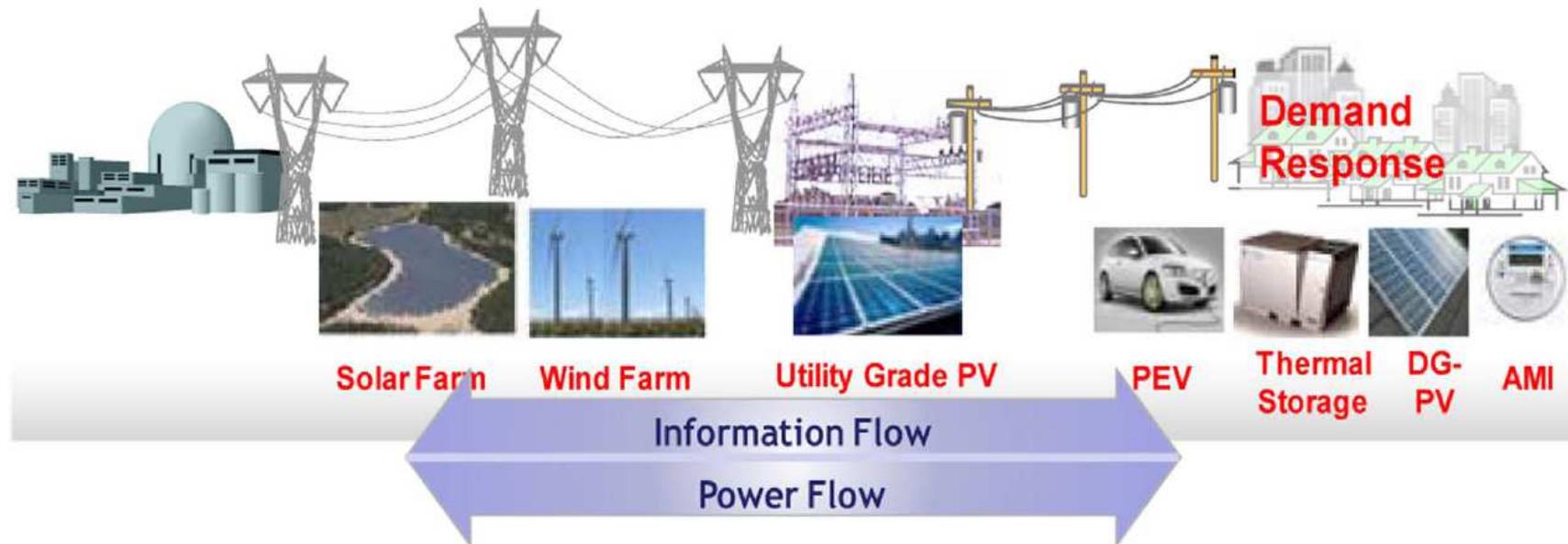
› Generation structure

- Centralised/business as usual
- Decentralised
- Mixed

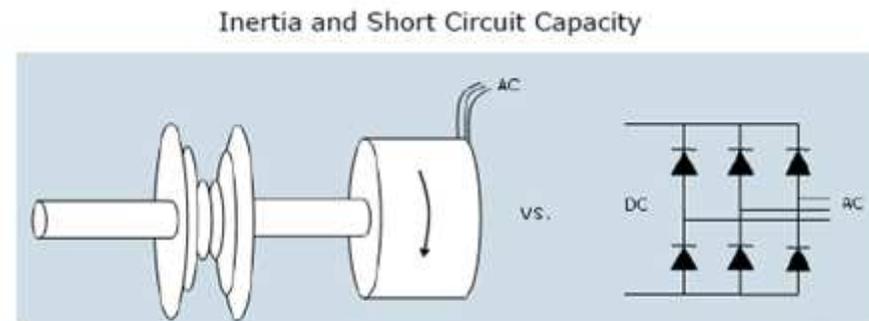
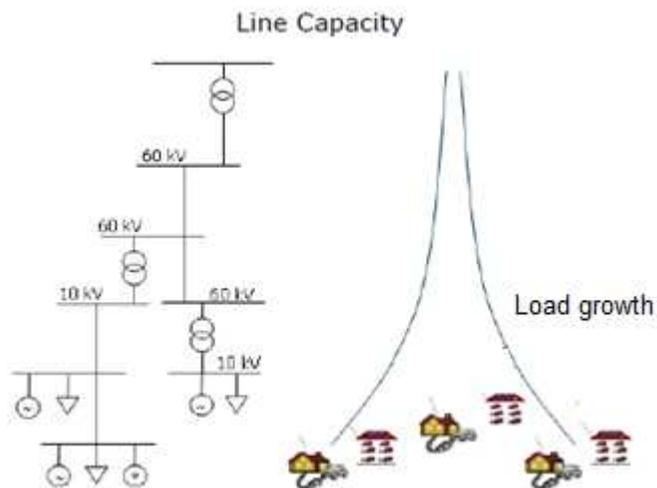
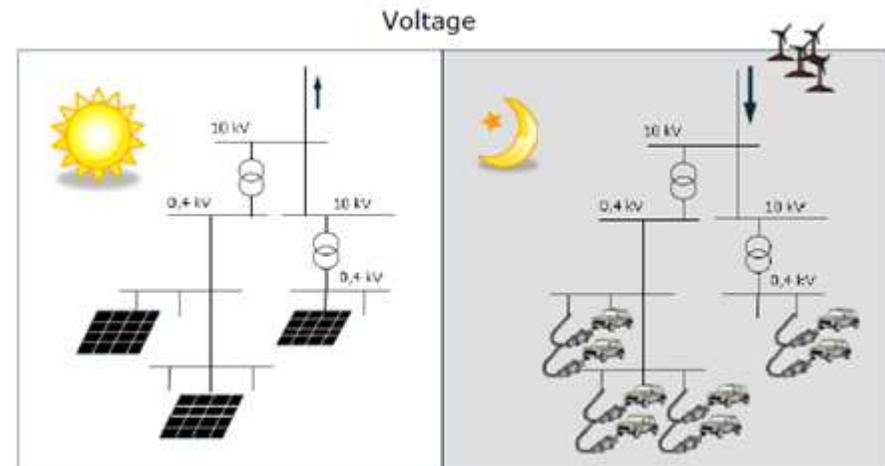
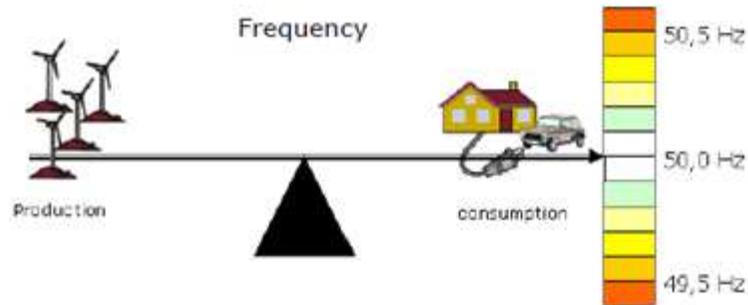
Future grid structure difficult to predict

1. CSIRO Future Grid Forum: Evaluating whole-of-system options for Australia's future electricity system (<http://www.csiro.au/Organisation-Structure/Flagships/Energy-Flagship/Future-Grid-Forum-brochure.aspx>)
2. AEMO report on 100% renewable electricity scenarios (<http://www.climatechange.gov.au/reducing-carbon/aemo-report-100-renewable-electricity-scenarios>)
3. Zero Carbon Australia: Stationary Energy Plan (<http://bze.org.au/zero-carbon-australia-2020>)
4. Ben Elliston, Iain MacGill, Mark Diesendorf (UNSW): "Least cost 100% renewable electricity scenarios in the Australian National Electricity Market", 2013. (<http://www.ies.unsw.edu.au/about-us/news-activities/2013/04/least-cost-100-renewable-electricity>)

- › Increased intermittency on the supply side
- › Communication network on top of physical one → cyber-physical system
- › Communication network all the way down to the household level
- › Automated demand response technically possible
- › Transmission, distribution and low-voltage systems will merge

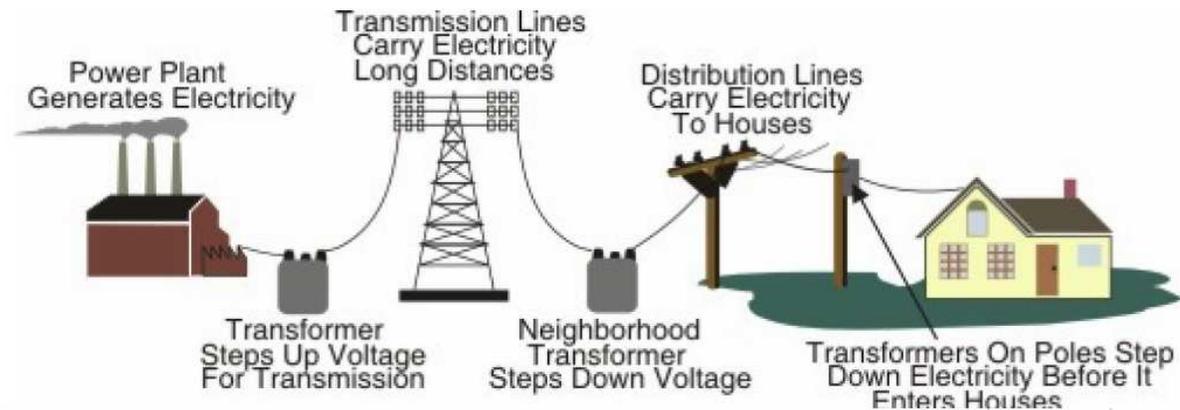


Issues with large penetration of renewables



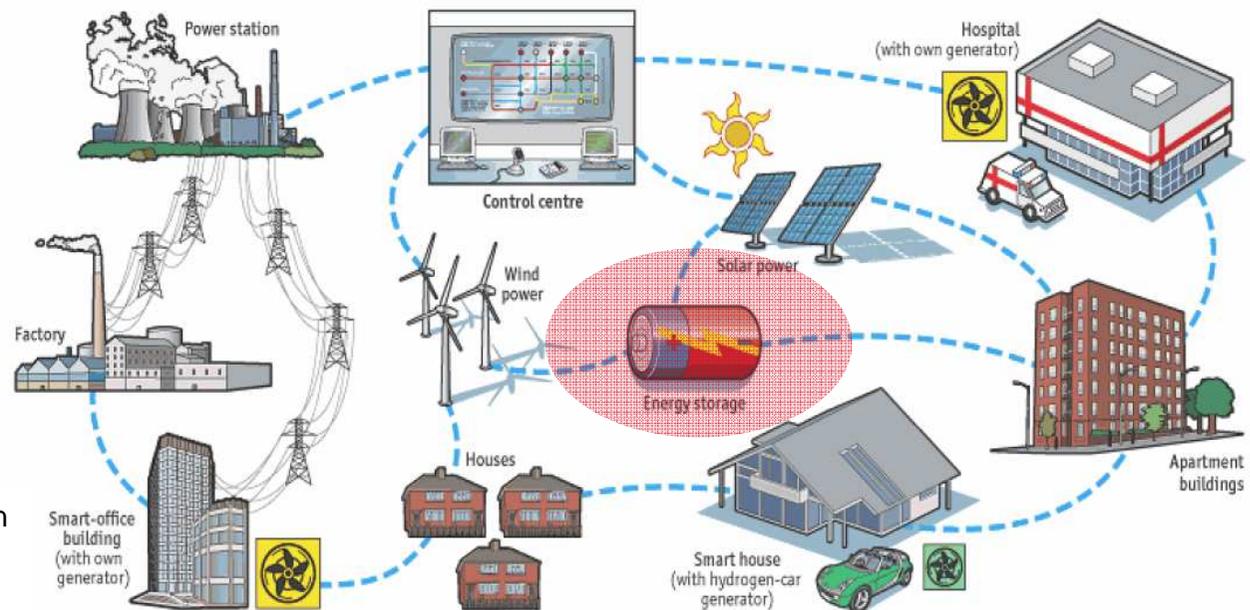
Before Smart Grid:

*One-way power flow,
simple interactions*



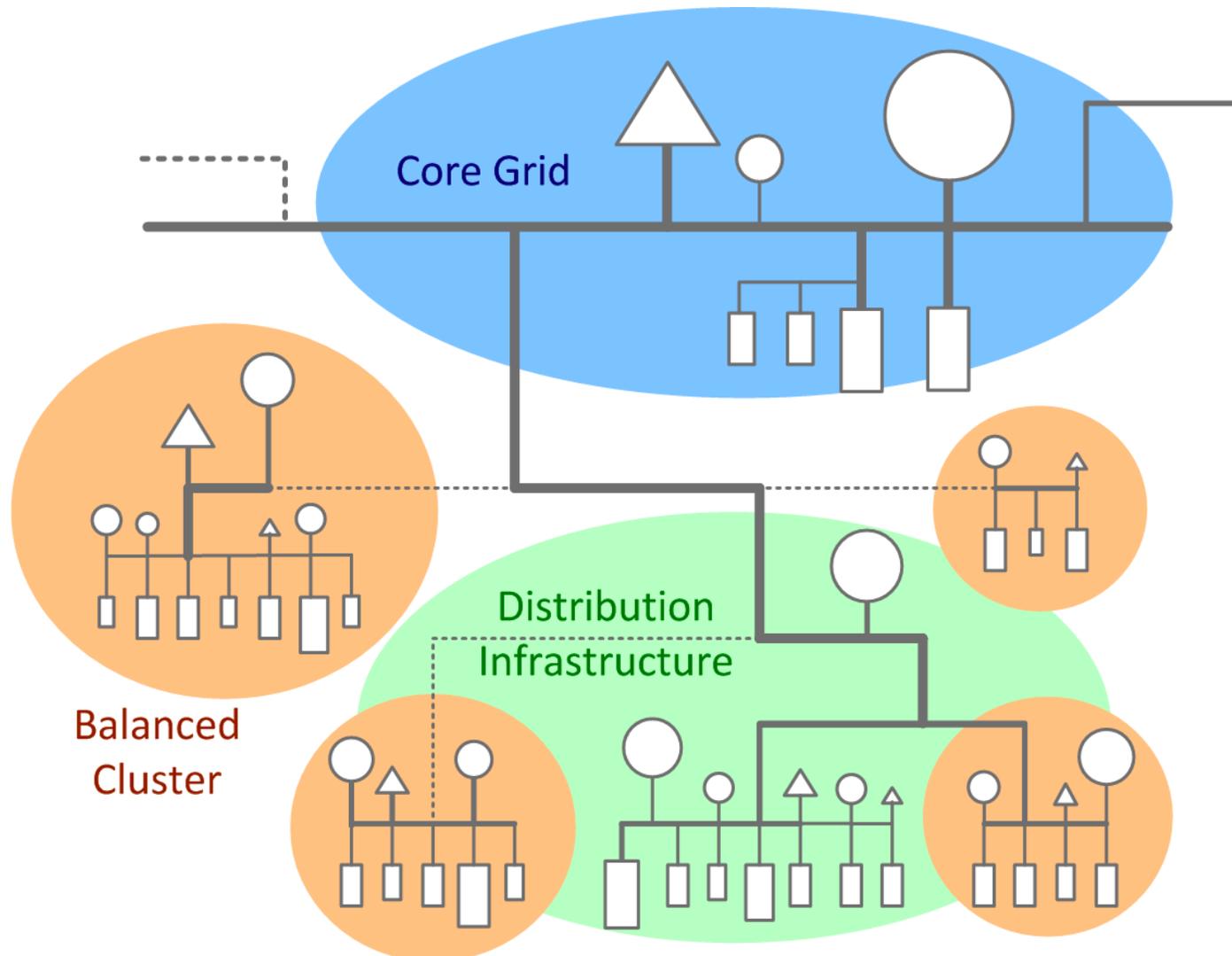
After Smart Grid:

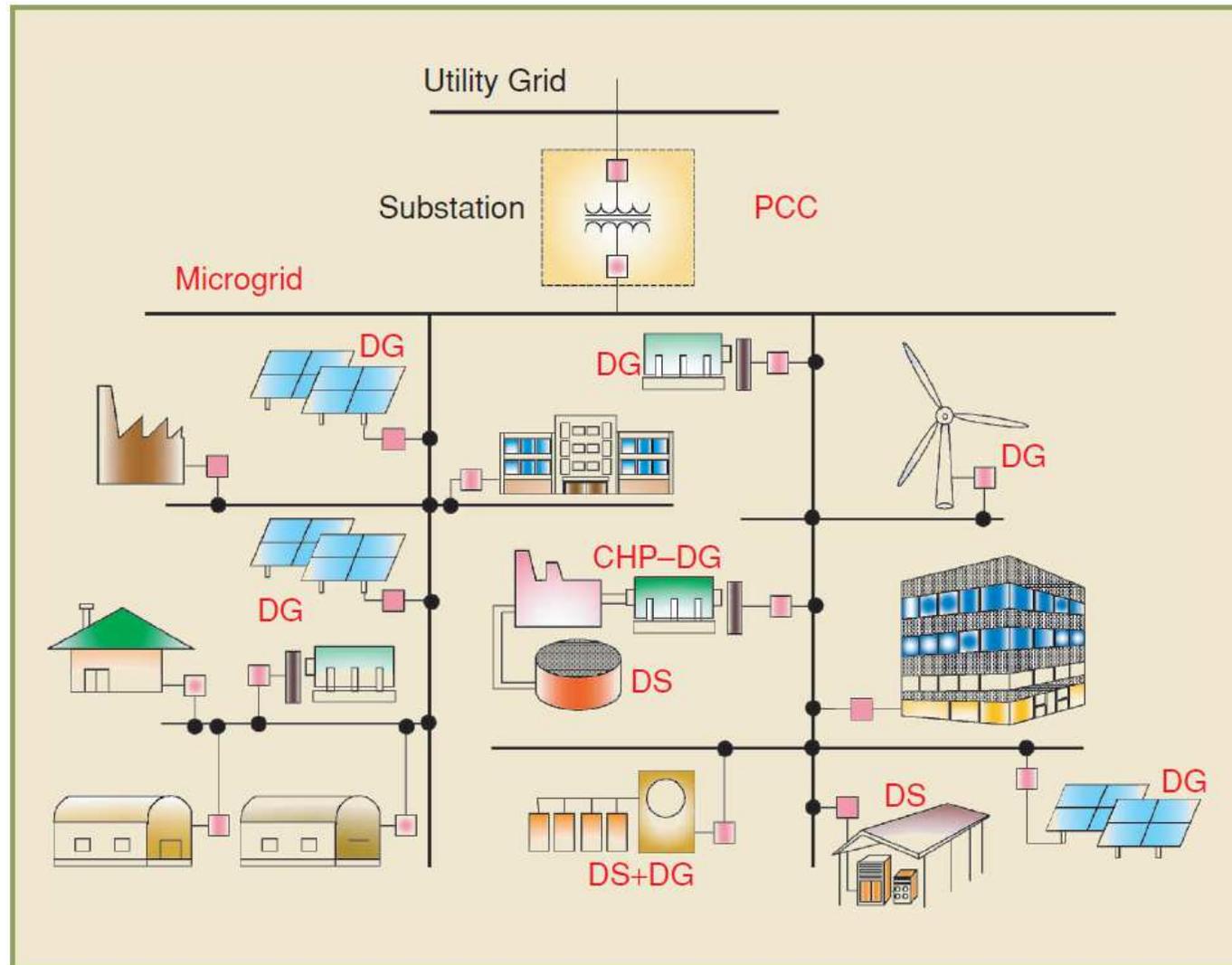
*Two-way power flow,
multi-stakeholder interactions*



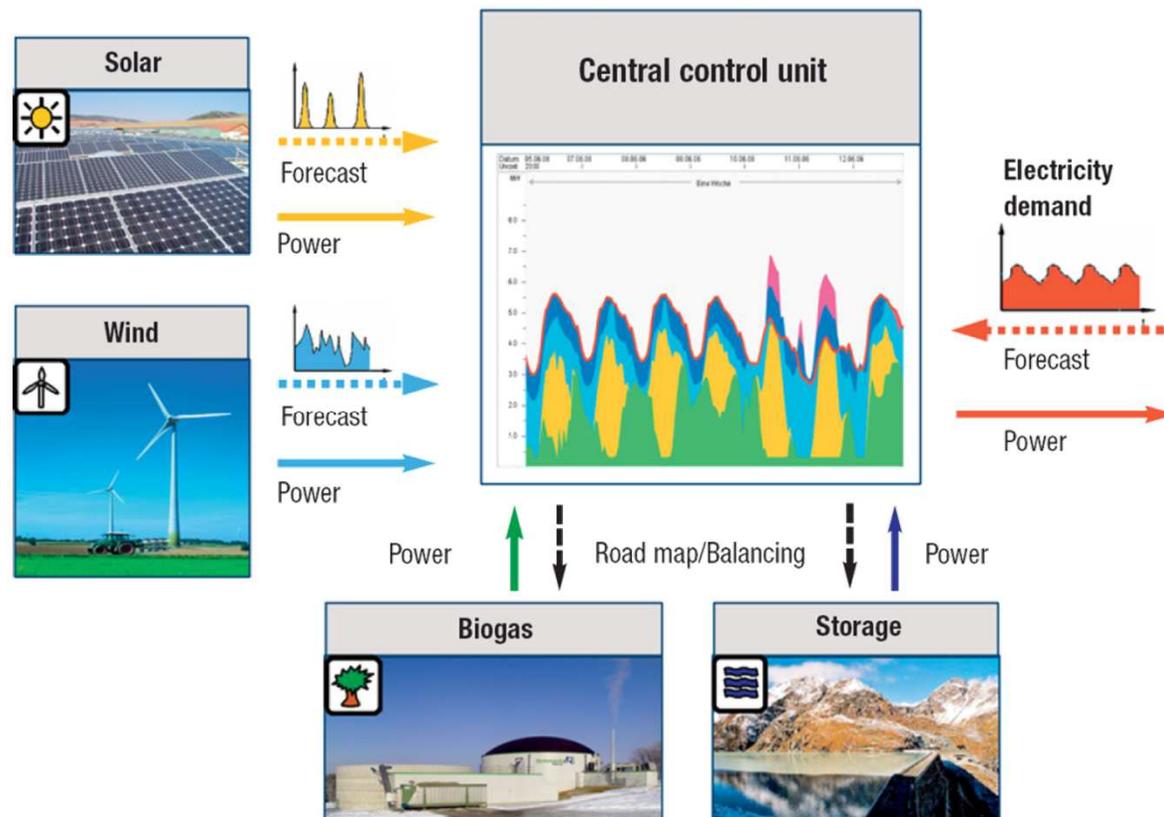
Source: AEP, 4th International Conference on Integration of Renewable and Distributed Energy Resources, Albuquerque, New Mexico, 6-10 December 2010.

Grid2050 Architecture (Bakken et al.)





- › A VPP is an aggregated system in which many DERs with small power generation output are partly or fully controlled by a single coordinating entity



Two extreme views

› Communication-based

- The 'big-computer+comms' model where almost everything possible will be measured and the data stored centrally as a first step.

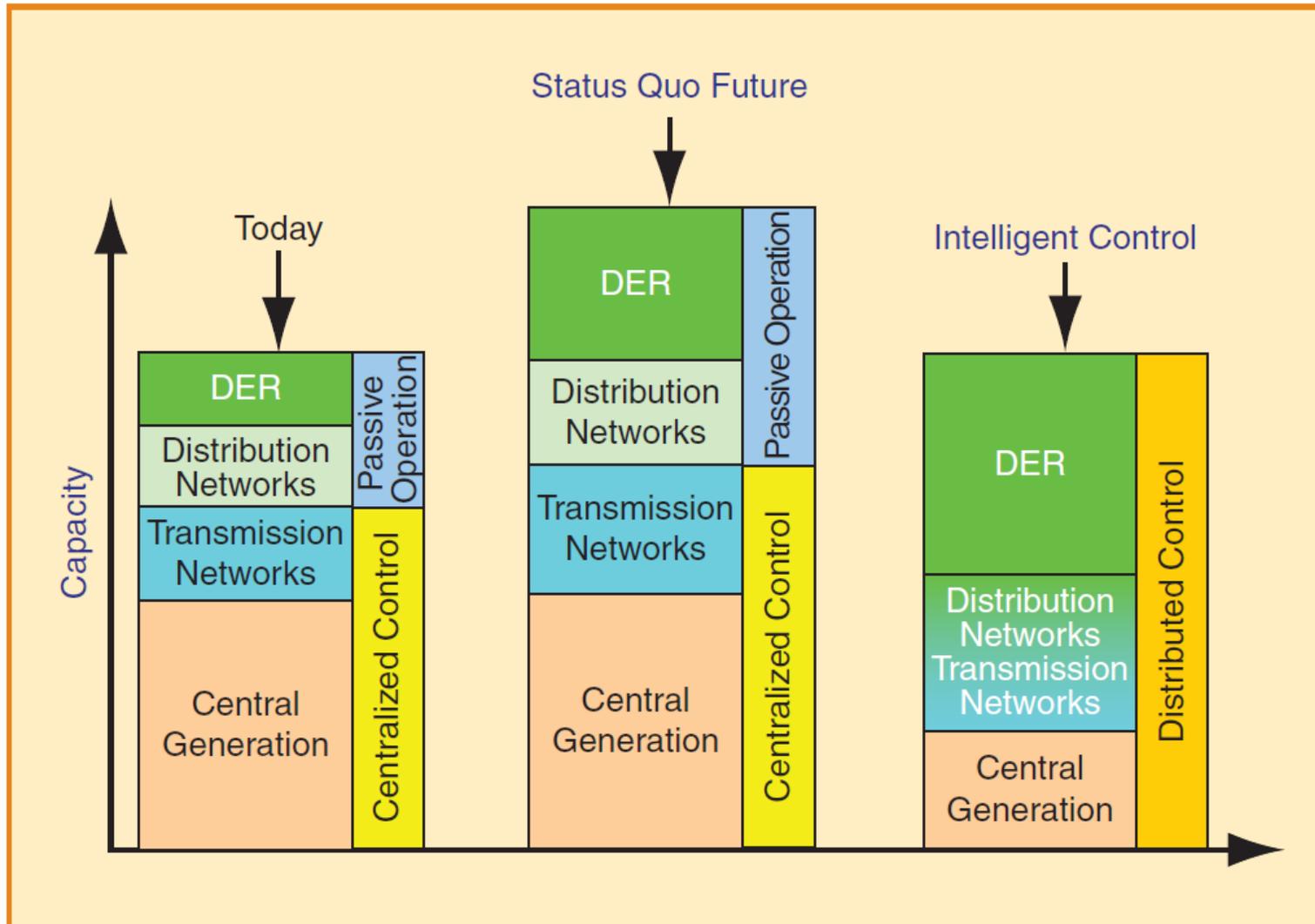
› Load-control-based

- 'Smart loads' are proposed to do almost everything we need!

How much loads can do depends on their degree of flexibility, i.e. energy storage capacity

	Old	New
Planning	Transmission follows generation	Generation follows transmission – energy highways?
Balancing	Generation follows load – dispatch	Load follows generation – demand response
Stability and control	Bulk system in control, aggregate load	Loads in control – granulated dynamics

The two paradigms will coexist in the foreseeable future



The role of storage in future grids



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Storage can serve different purposes (not only balancing!)

› At the **transmission** level

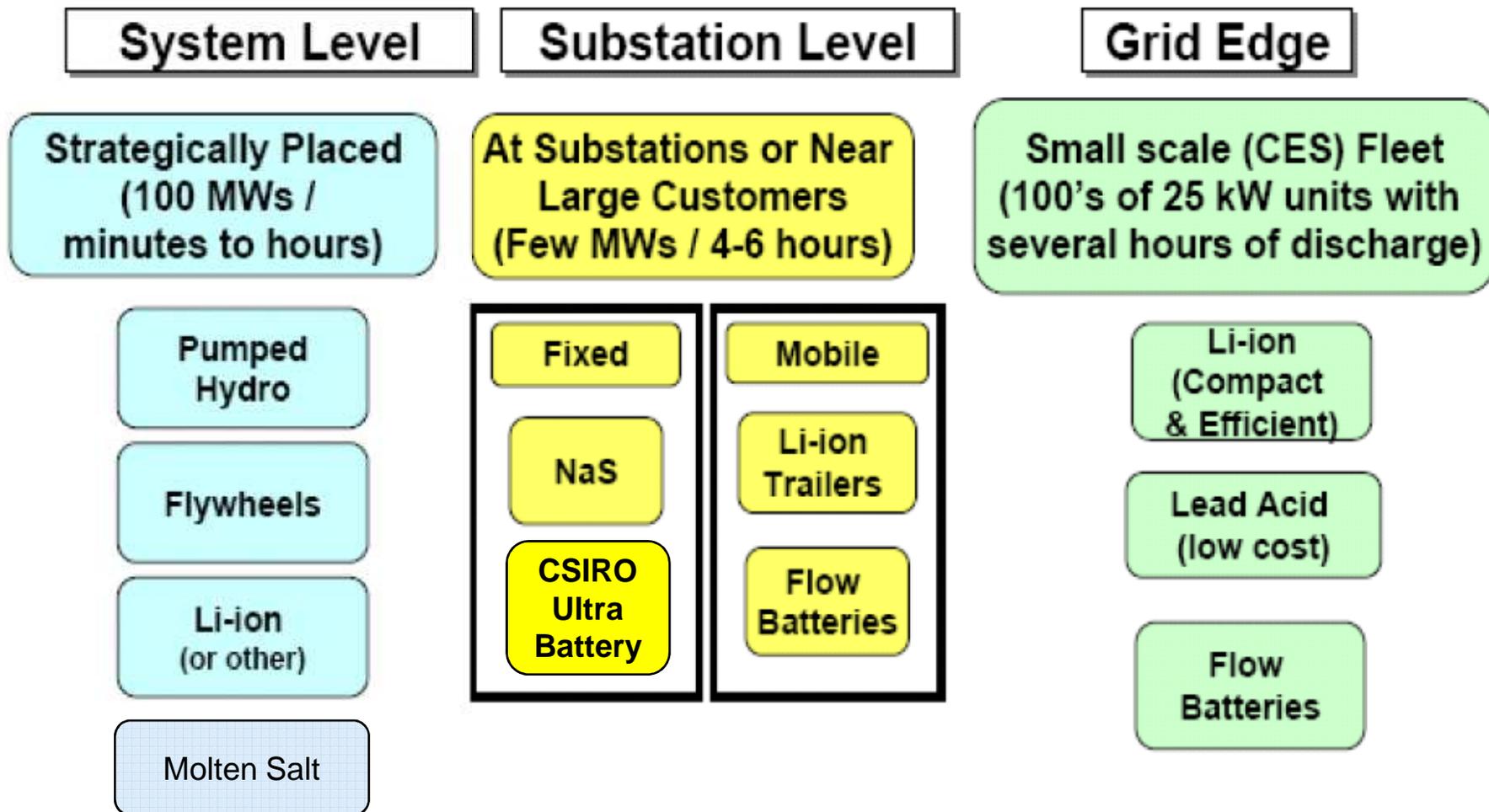
- Renewables capacity firming at different time scales (seconds-smoothing, minutes-shaping, hours/days-shifting), i.e. from power to energy
- Ancillary services

› At the **distribution/low voltage** level

- Peak shaving
- Voltage control
- Deferring grid upgrades

› At the **residential** level

- Residential PV shifting to avoid high prices
- Energy management in homes
- Participation in demand response
- Reliability: islanding/microgrids



› Technologies

- Pumped hydro, compressed air, flywheels, superconducting magnets, super capacitors, hydrogen, batteries

› Applications

- Energy (minutes & hours): diurnal load shifting, peak lopping, frequency regulation (spinning reserve)
- Power (milliseconds & seconds): power quality, frequency control, wind power smoothing (ramp rate limiting)

› Utility battery storage is still struggling to get traction

- Sodium-sulphur (NaS) batteries (NGK/Tsukuba Plant fire incident)
- Vanadium redox battery (25 years old technology but only a handful of installations)

› Proven technologies but still too expensive (except for pumped hydro and CAES), so only really got off the ground in niche applications

Commercially available battery technologies

		Specific Energy	Specific Power	Cell Cost	Cycle Life	C/D Efficiency
		(Wh/kg)	(W/kg)	(\$/kWh)	C/20/C/20 80% DOD	Input(Wh)/ Output(Wh)
Lead Acid	Flooded (Standard)	25	120	60	800	60%
	VLR/AGM/Gell	40	180	142	600	60%
	Carbon Matt	100	720	426	1200	70%
NiMH	Sint/Sint	51	3,150	650	1,600	98%
	Foam	90	1,800	550	1,400	90%
NiCd	Sint/Sint	60	1,500	500	1,900	98%
Li Ion	LiCoO ₂	185	1,500	1,000	700	70%
	LiMnO ₂	143	770	600	500	75%
	LiFePO ₄	200	1,400	700	4,000	90%
NaS		130	22	600	3500	90%
NiZn		100	900	500	300	85%
Flow Battery	Vanadium Redox	10	6	500	10,000	60%
	Zinc Bromide	85	55	600	10,000	60%

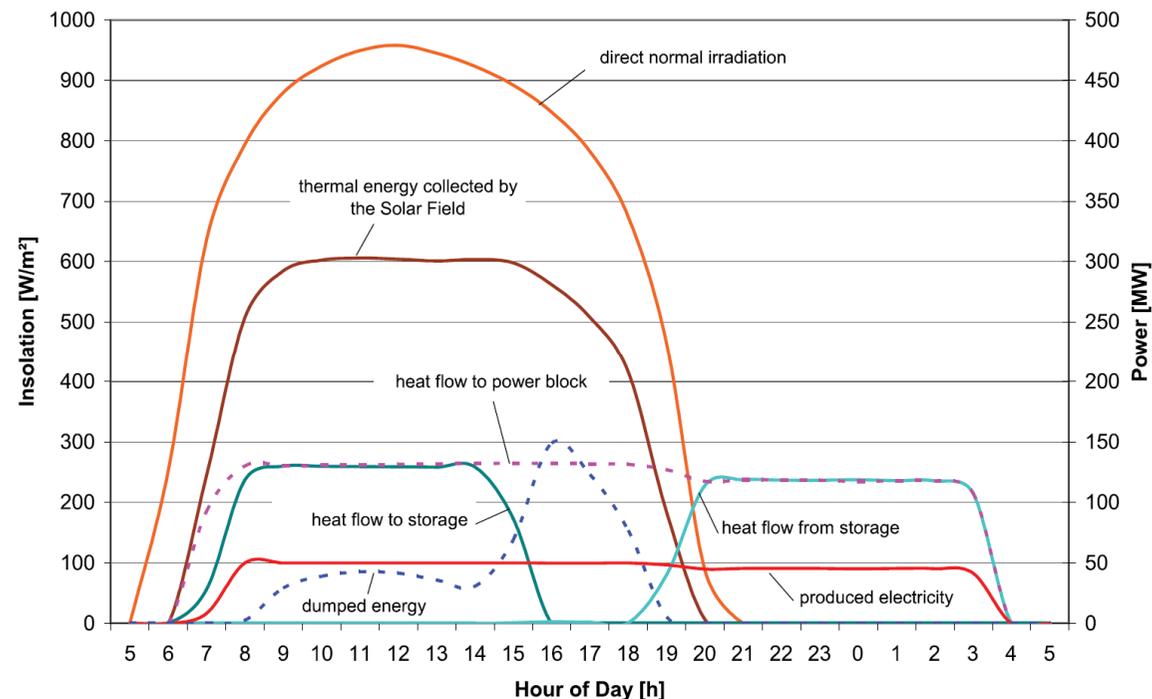
According to the US National Labs:

- **Energy storage costs** (renewables capacity firming, load following, time shift): < \$200/kWhr
- **Power storage costs** (wind Integration, area regulation): < \$500/ kWhr

James P. Lyons, Timothy D. Mount, Richard Schuler, and Robert J. Thomas, "The Multidimensional Character of Electric Systems Storage", 2013 IREP Symposium-Bulk Power System Dynamics and Control –IX (IREP), August 25-30, 2013, Rethymnon, Greece.

Molten salt storage (coupled with CSP)

- › Energy is stored before energy conversion (heat → electricity) has taken place, much like hydro with a dam
- › Long-term storage losses less than 1% of stored heat per day
- › Commercially available technology (Andasol solar power plant in Spain has been in full-scale commercial operation since 2008)



Source: Australian Sustainable Energy Zero Carbon Australia Stationary Energy Plan 2010

- › Distributed (residential, commercial) battery storage, on the other hand, is likely to experience a boom in the near future
- › Doesn't need to compete with utility rates but rather commercial/residential rates so "socket parity" much easier to achieve
- › Natural fit to residential and commercial PV systems
- › Boom on the horizon
 - Financial incentives in Germany
 - Vector's home solar electricity system
 - Smart homes

Residential battery storage

- › Panasonic 1.35 kWh lithium-ion battery
 - lifetime of 5000 load cycles at 80% DOD (depth of discharge)



- › Toshiba's 6.6kWh "SCiB" lithium-ion battery
 - On a full charge, the Toshiba system is reportedly capable of powering lighting equipment (100W), refrigerator (160W), TV (150W) and personal computer (30W) for about 12 hours



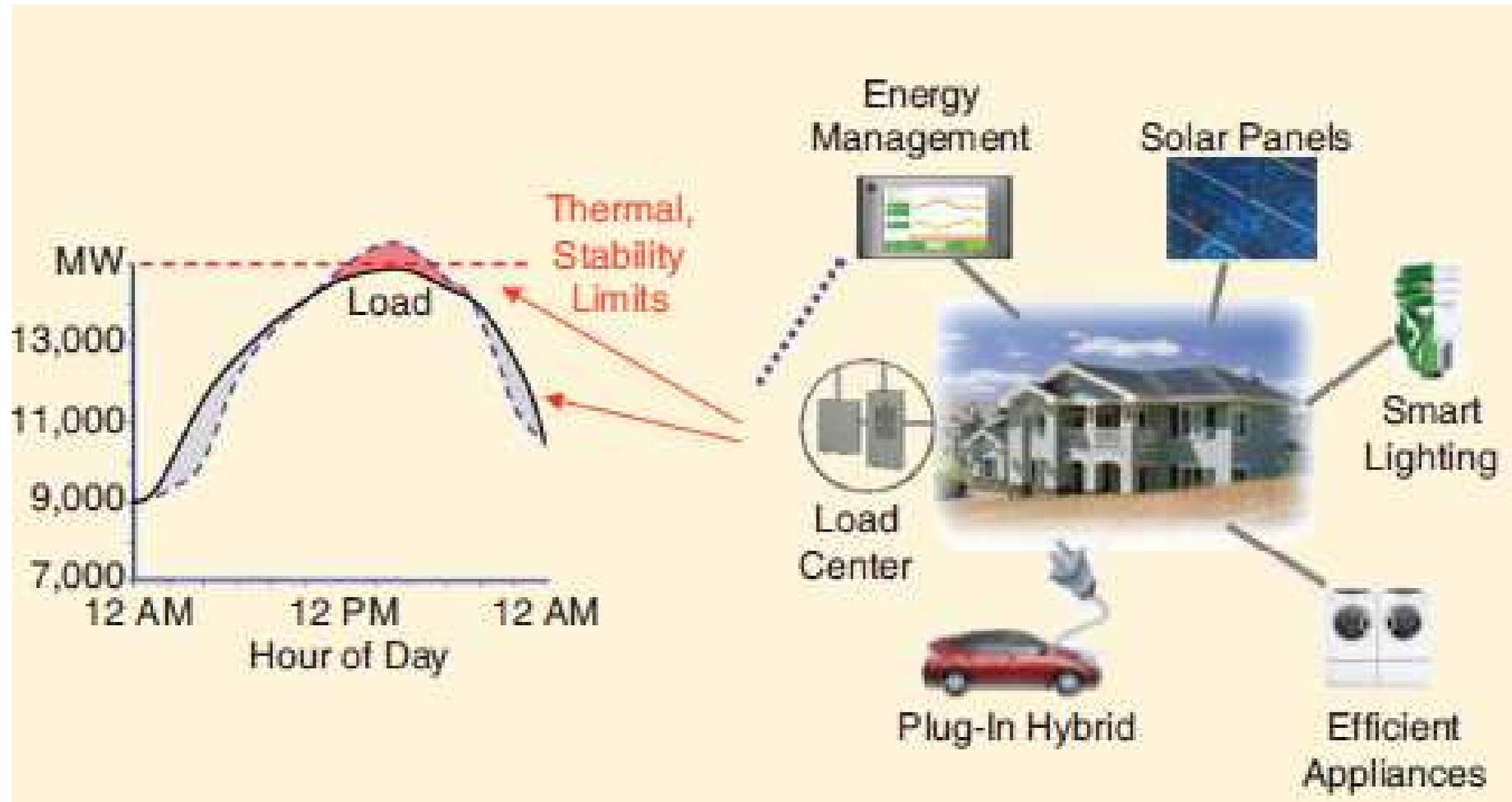
Source: Phys.org

› RedFlow R510 5 kW/10 kWh Zinc-Bromine flow battery



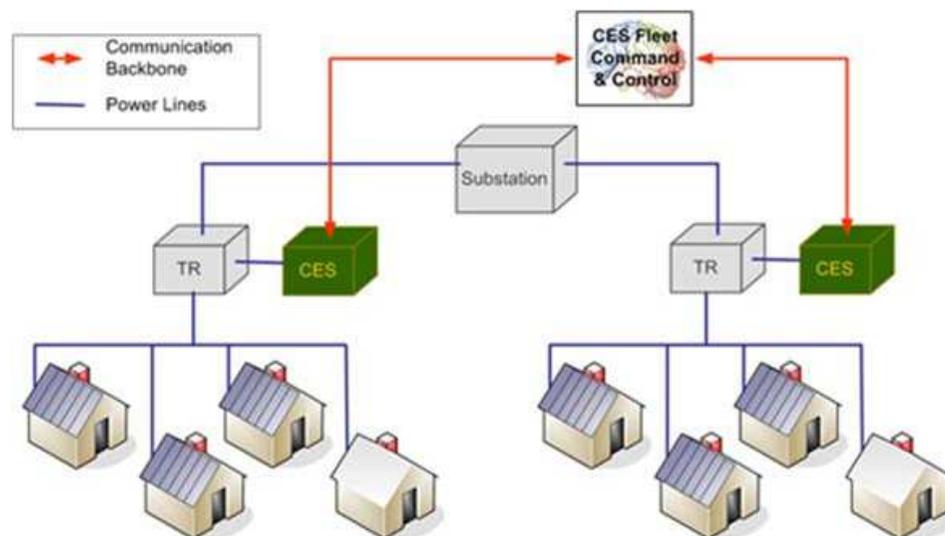
- ▶ 5kW, 10kWh energy storage
- ▶ Certified for connection to grid and residential solar PV
- ▶ Smart Grid compatible, with 20 msec response time
- ▶ Slim, under eaves design
- ▶ Highest quality components
- ▶ Intelligent microprocessor to manage local supply/demand and for remote access
- ▶ Plug-and-play installation

Source: <http://www.redflow.com.au>



Source: J.Fan and S.Borlase, IEEE Power & Energy Magazine, Vol 7, NO 2, 2009

- › Small in size providing 1-2 hours of backup power for a neighbourhood
- › Connected on the low-voltage side of the distribution transformer
- › Can also be used for voltage control
- › American Electric Power's Community Energy Storage (CES) program
 - 25kW/75kWh Li-Ion batteries



Source: www.freedm.ncsu.edu



Source: www.renewableenergyworld.com

Alternative storage options

- › We need energy buffer
- › Battery storage is expensive
- › Why not harness inherent flexibility of loads:
 - Thermal inertia of buildings Demand response
 - Cyclable and shiftable loads
- › And generators:
 - Kinetic energy in the rotating masses of wind turbines

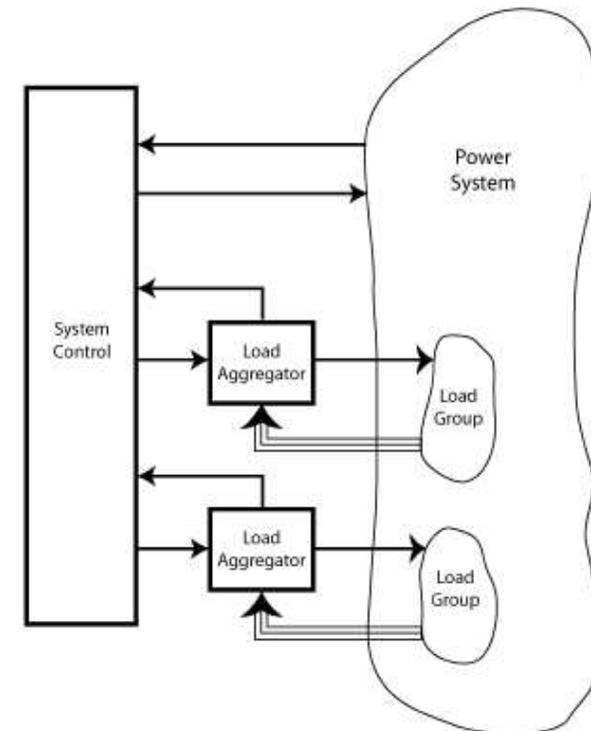


Fig. 6. Schematic representation of a hierarchical load control strategy.

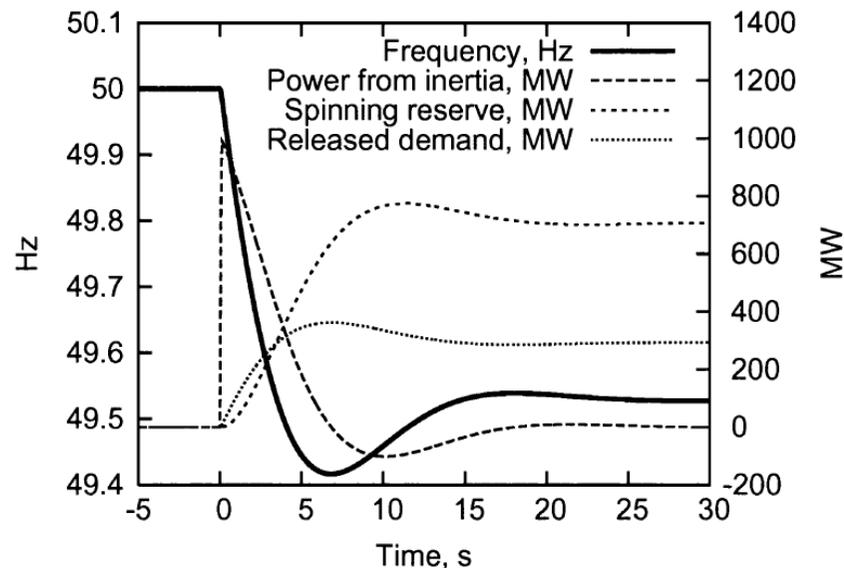
Ref: Calloway and Hiskens, Proc IEEE, 2011

- › DR can offer both contingency and regulation frequency control (FC).
- › On the **shorter time scale**, loads can provide “virtual” (or negative) frequency response if they correlate their power consumption to the grid state in an automatic “droop control” manner.
- › On a **minutes to hours time scale**, FC is provided by load shifting (e.g. dish washers and washing machines) and load cycling (e.g. HVAC).
- › Energy storage (e.g. electric vehicles and batteries) can greatly increase the capability of DR to provide FC by providing the necessary energy buffer.
- › ‘Smart loads’ (or smart homes) are likely to emerge as DR building blocks.

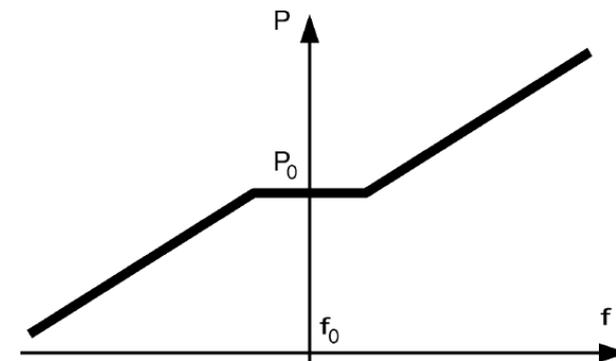
Short, J.A.; Infield, D.G.; Freris, L.L.; , "Stabilization of Grid Frequency Through Dynamic Demand Control," Power Systems, IEEE Transactions on , vol.22, no.3, pp.1284-1293, Aug. 2007

Palensky, P.; Dietrich, D.; , "Demand Side Management: Demand Response, Intelligent Energy Systems, and Smart Loads," Industrial Informatics, IEEE Transactions on , vol.7, no.3, pp.381-388, Aug. 2011.

- › Frequency-responsive loads can be a reliable and very inexpensive provider of frequency response.
- › Any device with some inherent energy storage is a suitable candidate, e.g. refrigerators, freezers, air conditioners, water heaters, some pumps, and heating systems.



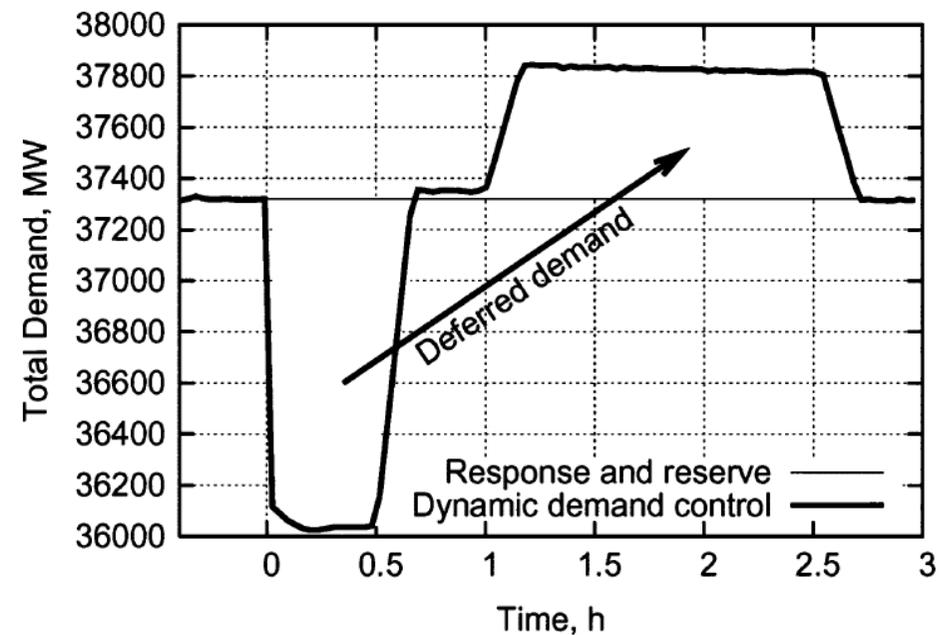
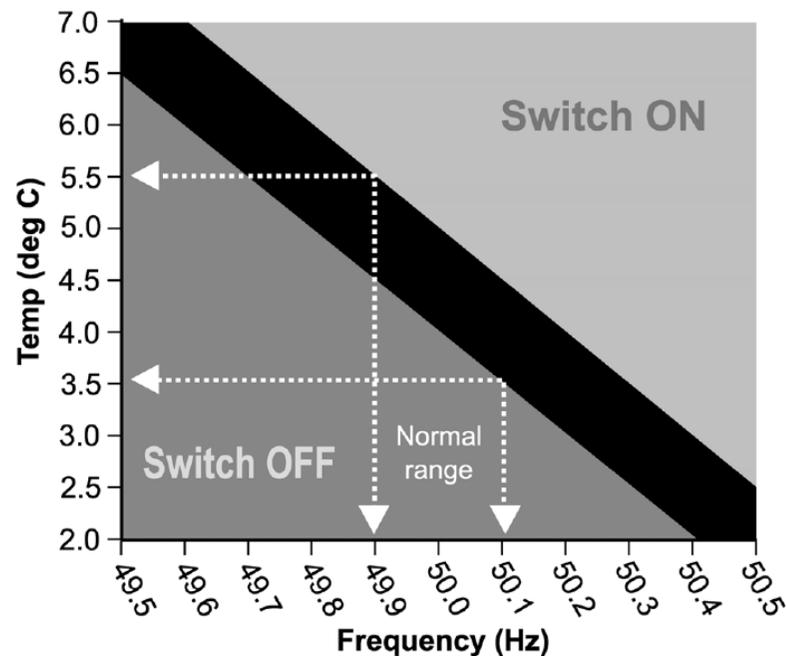
Frequency event following a load increase



Frequency-responsive load

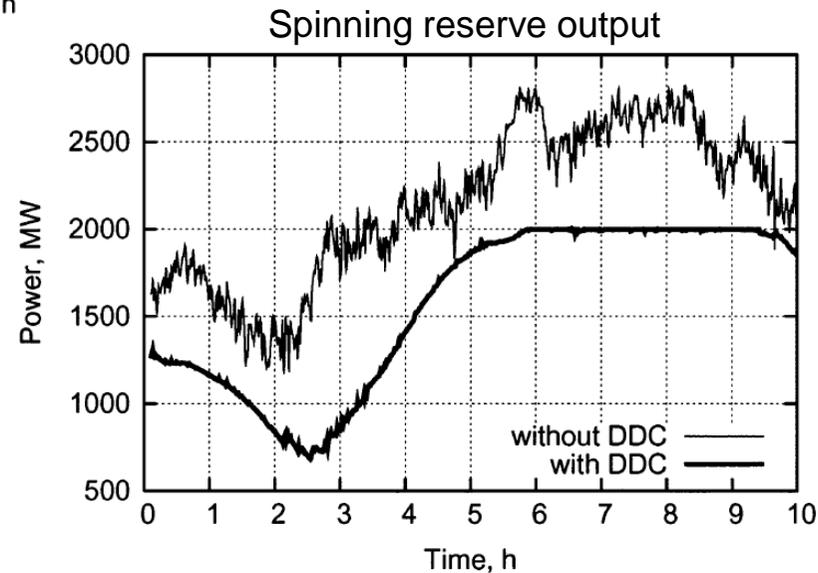
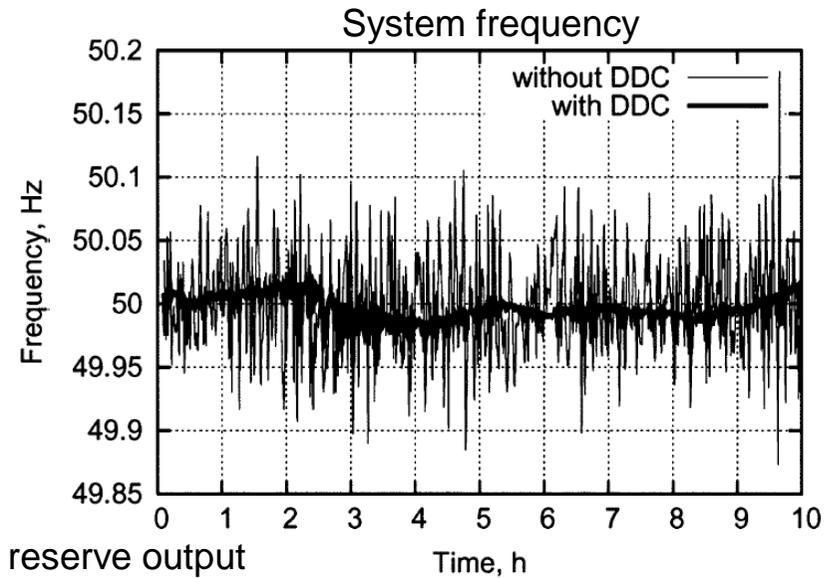
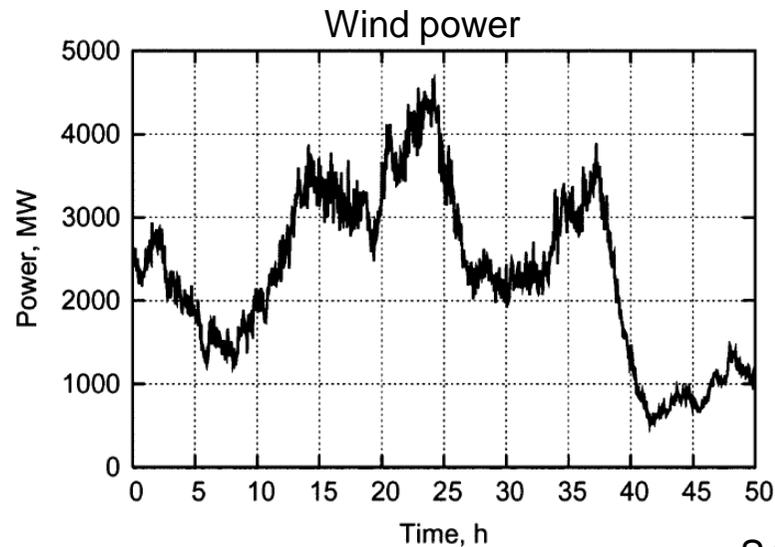
Example: dynamically controlled refrigerator

- › Following a frequency event, the fridge temporarily reduces its thermostat settings, which results in a slight increase in temperature.
- › The 'borrowed' energy is then taken back after the frequency has settled.



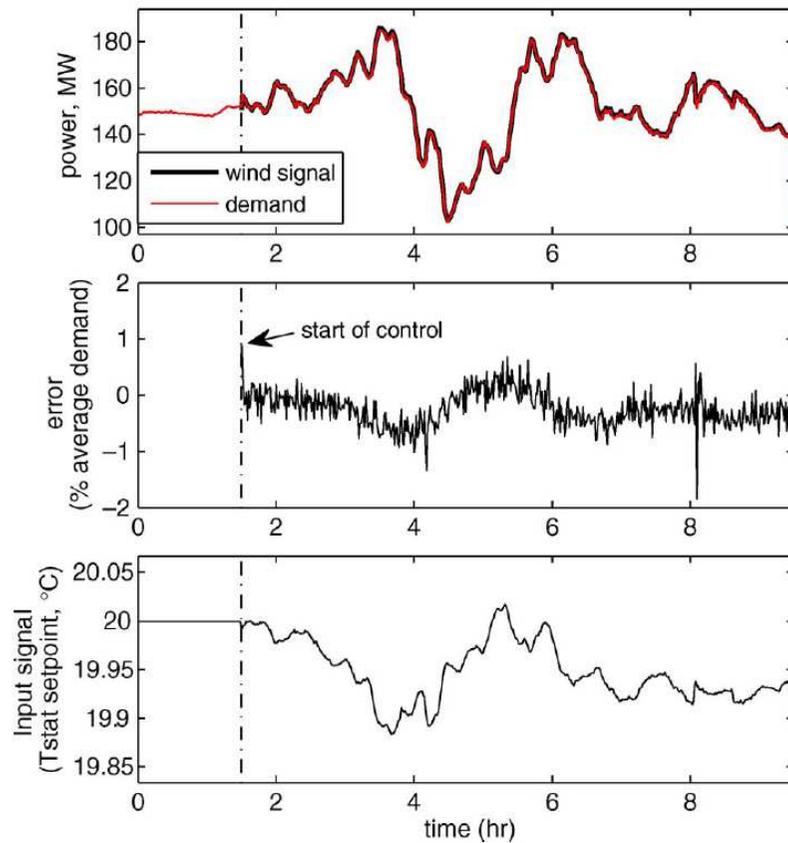
Short, J.A.; Infield, D.G.; Freris, L.L.; , "Stabilization of Grid Frequency Through Dynamic Demand Control," Power Systems, IEEE Transactions on , vol.22, no.3, pp.1284-1293, Aug. 2007.

Wind intermittency with DDC

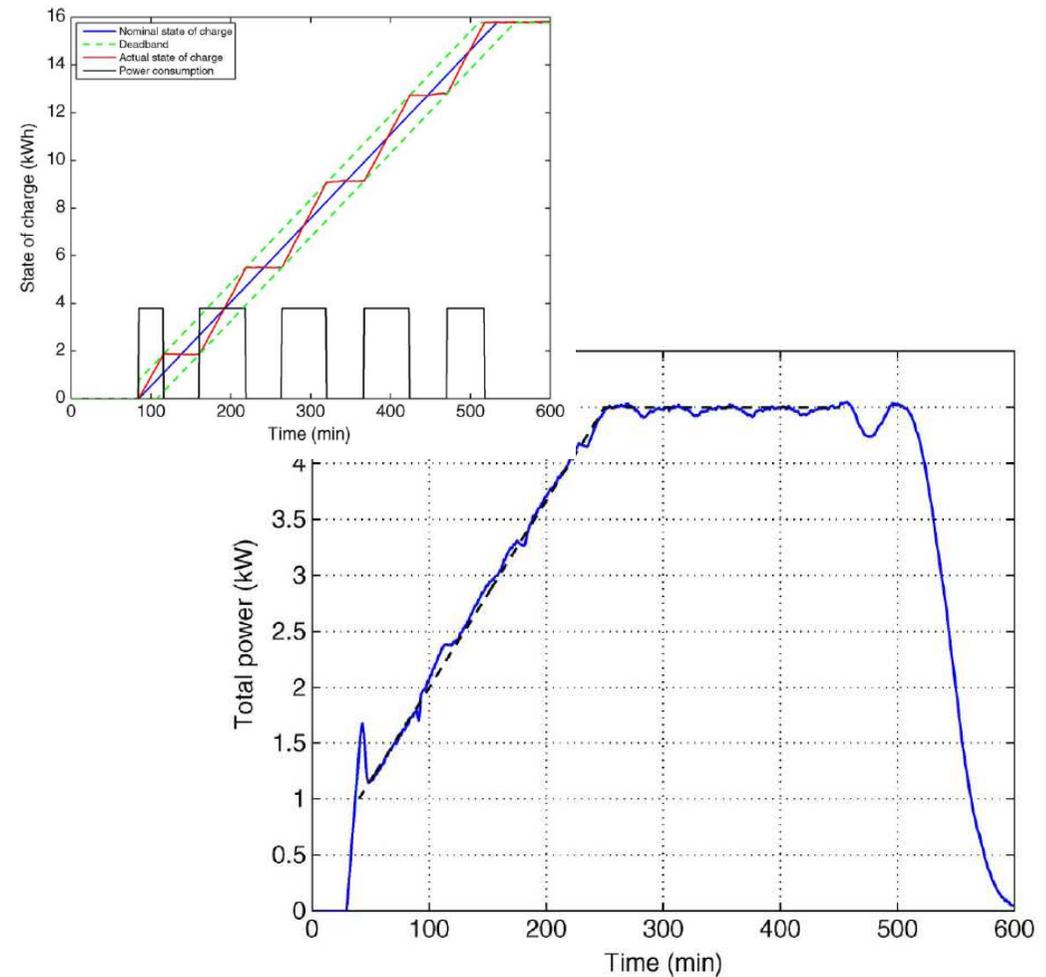


Short, J.A.; Infield, D.G.; Freris, L.L.; ,
"Stabilization of Grid Frequency
Through Dynamic Demand Control,"
Power Systems, IEEE Transactions on ,
vol.22, no.3, pp.1284-1293, Aug. 2007.

Manipulate thermostat set point

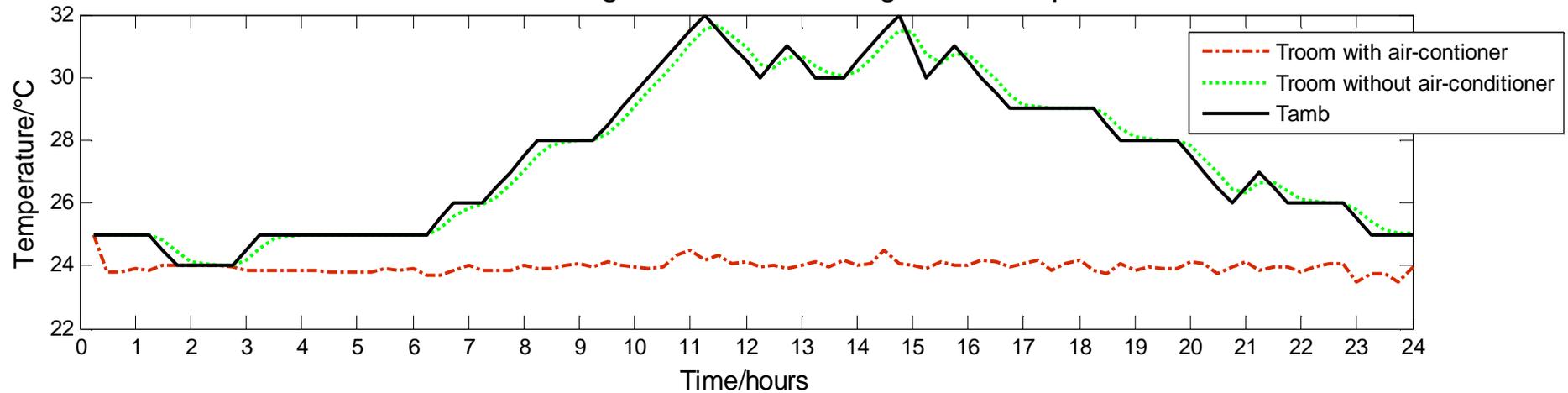


Hysteresis-based PEV charging scheme

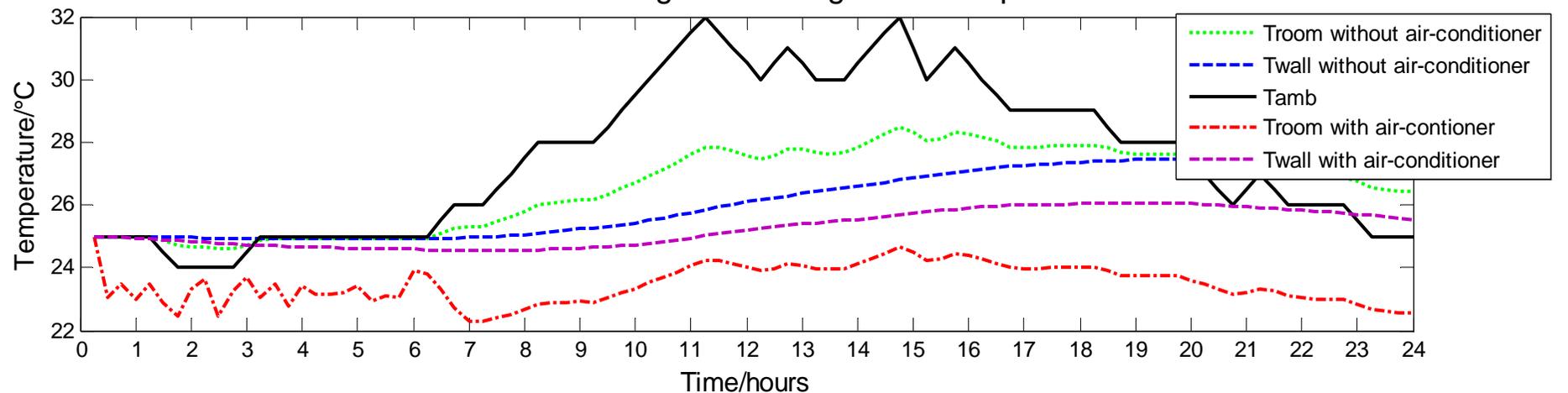


Ref: Calloway and Hiskens, Proc IEEE, 2011

Thermal behaviour of the building without considering thermal capacitance of the wall



Thermal behaviour of the building considering thermal capacitance of the wall

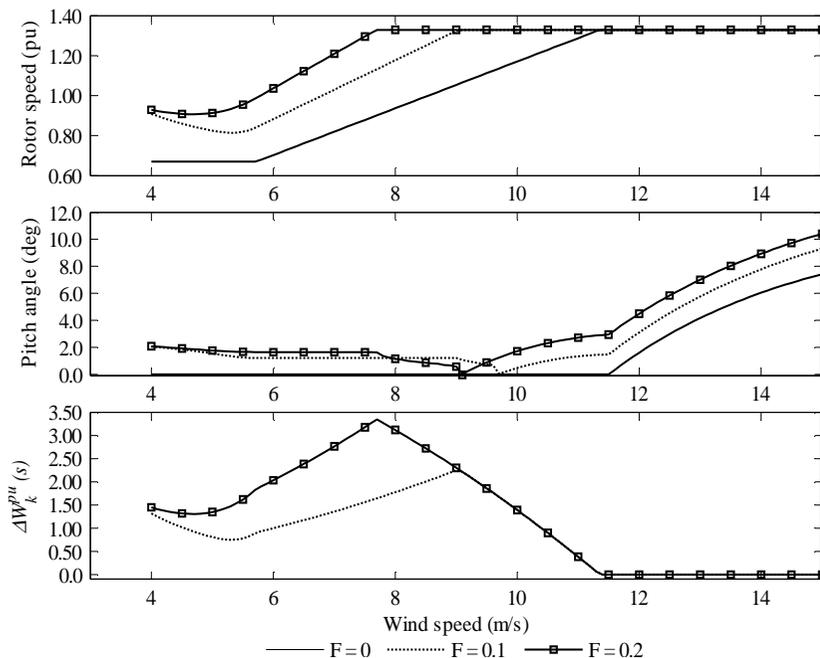


- › Why not modulate the kinetic energy in the rotating masses of wind turbines to smooth out the output?

$$W_k = \frac{1}{2} J \omega^2$$

Wind turbines have per unit inertia higher than synchronous generators

Rotational speed can be easily controlled in modern wind turbines



Use wake interaction

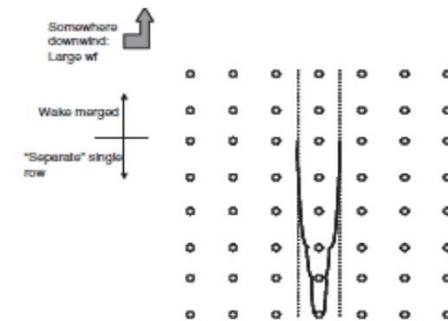


Figure 1. Illustration of the regimes of the proposed model. The wind comes from the 'south', parallel to the direction of the rows

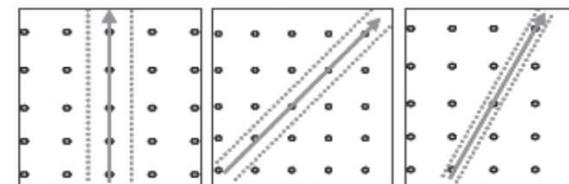
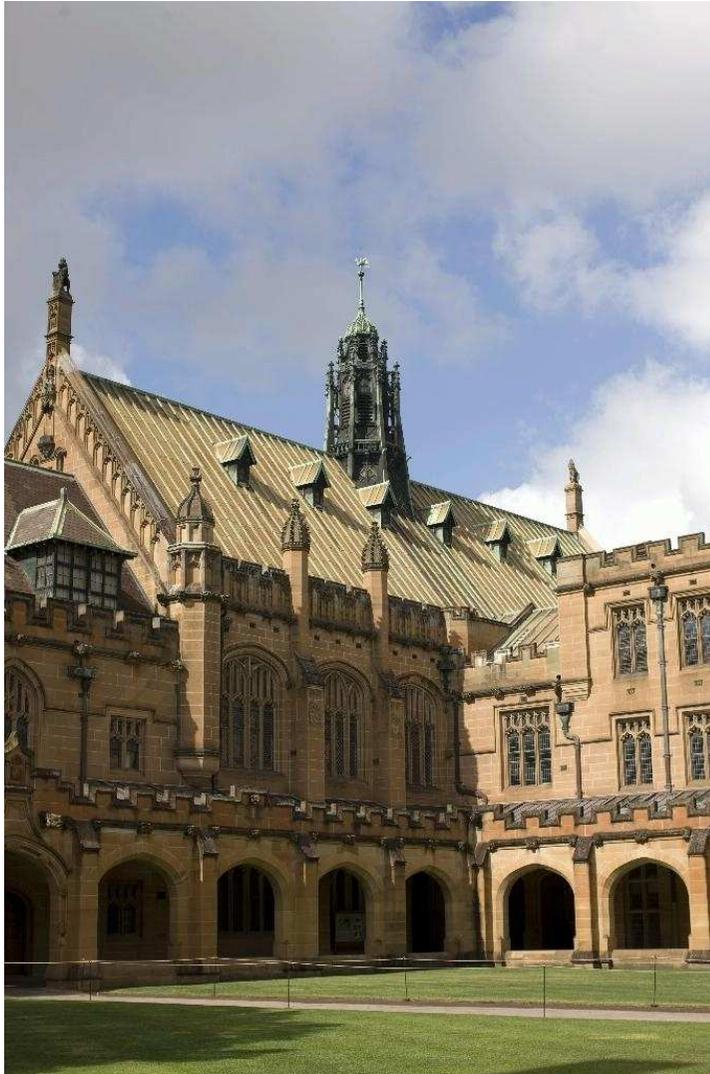


Figure 2. Examples of wind turbine patterns for different wind directions

- › A sustainable energy future will need to rely on intermittent energy sources.
- › We'll need energy buffer to keep supply and demand in perfect balance.
- › In countries like Australia with the population concentrated in a small number of large cities, it won't be possible to generate all the electric power locally.
- › Hence, some sort of central generation will be needed, which will require grids (of some sort).
- › Likely scenarios will include a combination of central generation plus increasingly self-sufficient local clusters (smart homes, micro grids) where battery storage will play an important role.
- › Wherever possible, 'low-marginal-cost' solutions will be used.



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