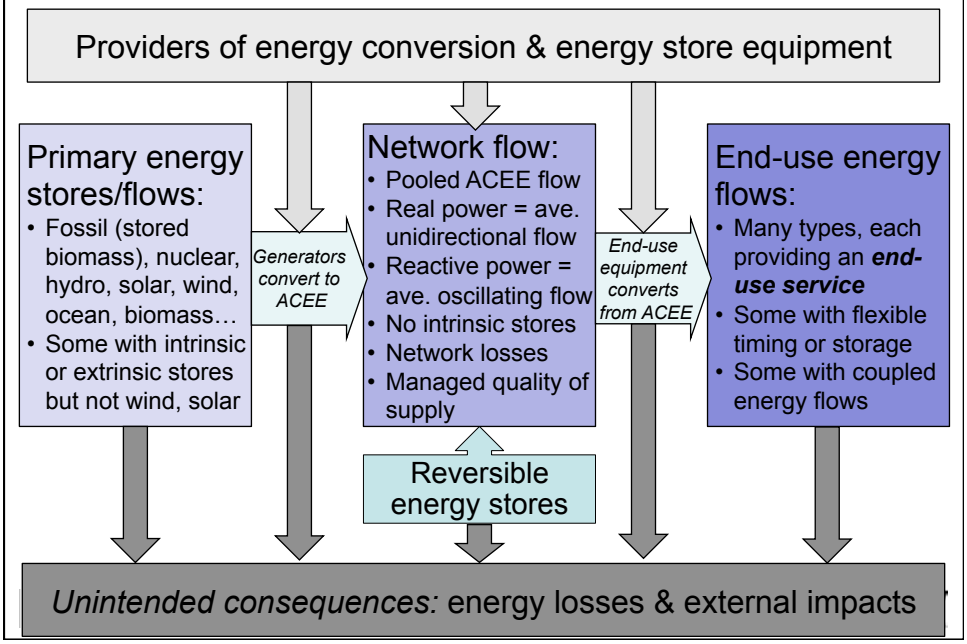
Implications of high-penetration solar & wind generation & energy storage for the National Electricity Market

Australian Institute of Energy Seminar, Sydney, 28/4/16

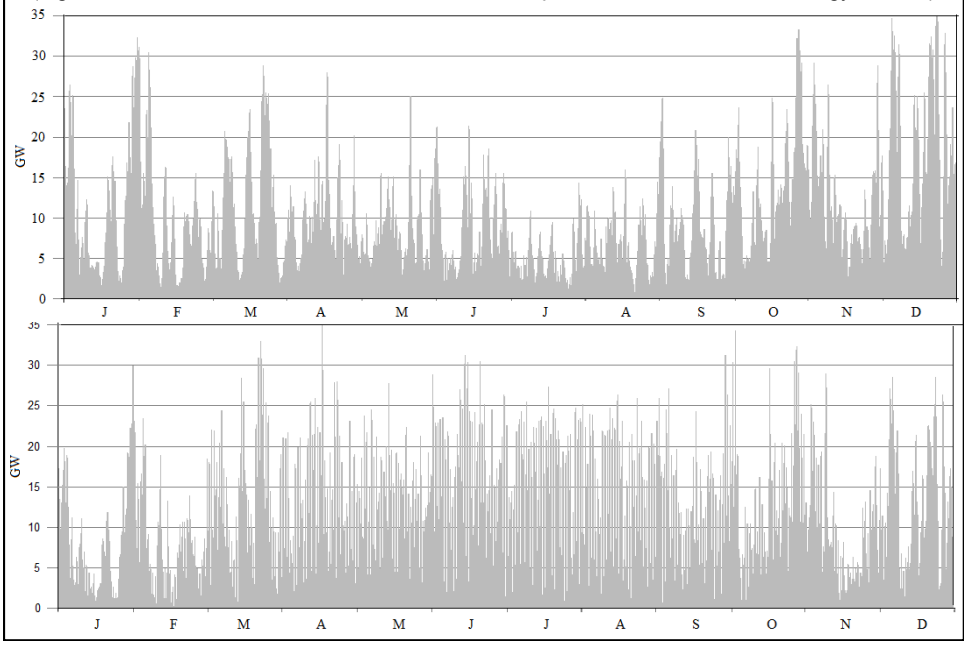
Hugh Outhred
University of New South Wales and Ipen Pty Ltd

The scope of this talk will be more fully addressed in Australian Energy Week Learning Session D, 20/6/16
http://www.questevents.com.au/australian-energy-week-2016/depth-learning-sessions

Electricity industry enacts an energy conversion chain via pooled alternating current electrical energy (ACEE) flowing in a network

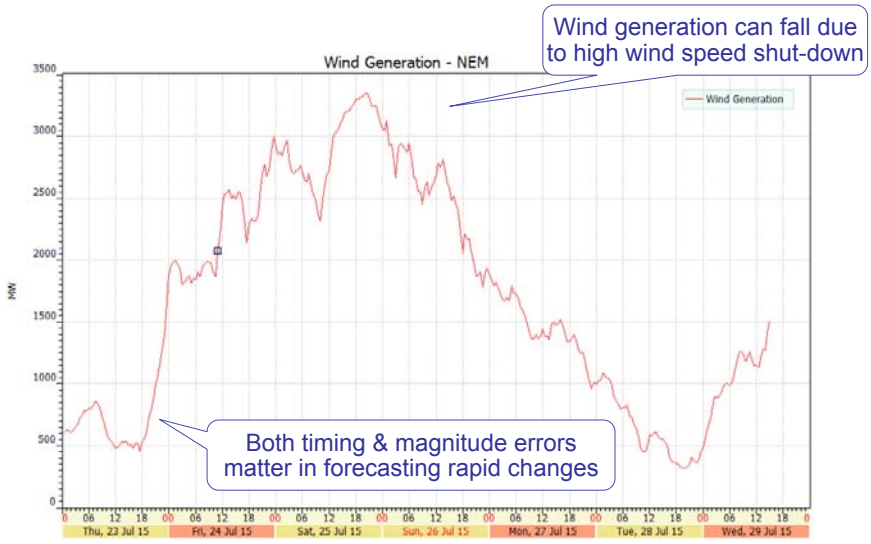


Top: Wind generation (GW) in Denmark, Germany, Netherlands and UK, 2013
Bottom: Combined wind & solar generation (GW) in Germany, 2013
(Figs 6 & 13 in *How Much Wind And Solar Can Norway's Reservoirs Balance?*, Energy Matters)



Wind generation in the NEM (MW), July 2015

(Falcon, AEMO, Can renewable energy meet 'baseload' power?, 19/8/15)
http://grattan.edu.au/events/can-renewable-energy-meet-baseload-power/



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Killinger et al, Impact of the Solar Eclipse from 20th March 2015 on the German Electrical Supply - Simulation and Analysis

Energy Technology, Feb 2016, http://onlinelibrary.wiley.com/doi/10.1002/ente.201500228/full

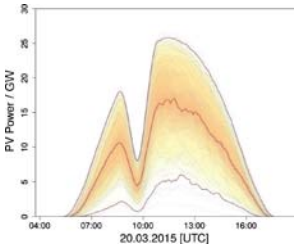


Figure 4. The PV-generated power in Germany over 84 different days during a simulated solar eclipse in the morning. The 5, 50, and 95 % percentiles are each displayed as red lines.

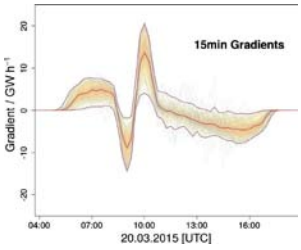


Figure 6. Gradients during a simulated solar eclipse in the late morning hours, occurring for 15 min on 84 different days. For an easier comparison, the gradients have been upscaled to GW h^{-1}. Note: Due to this upscaling, the indicated values do not indicate an occurrence of these gradients for one hour, but rather still only for 15-minute intervals. The 5, 50, and 95 % percentiles are each displayed as red lines.

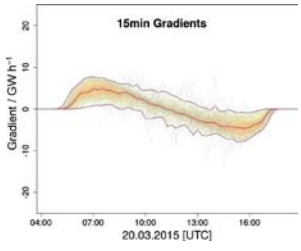


Figure 5. Gradients lasting for 15 min on 84 different days, without the effects of a solar eclipse. For an easier comparison, the gradients have been upscaled to GW h^{-1}. Note: Due to this upscaling, the indicated values do not indicate an occurrence of these gradients for one hour, but rather still only for 15-minute intervals. The 5, 50, and 95 % percentiles are each displayed as red lines.

Actual outcome: Figures 7 & 8 below imply that neighbouring countries provided most of the dynamic response

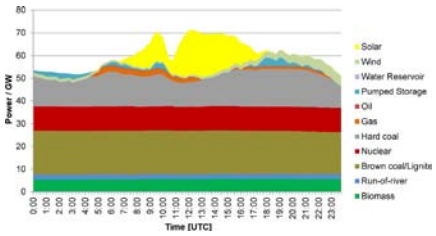


Figure 7. Energy generation by different technologies in Germany on March 20th (based on Ref. [17]).

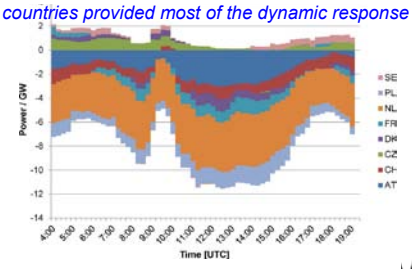
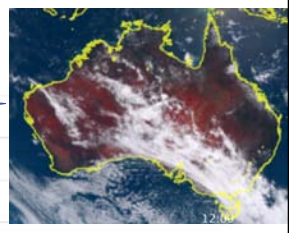


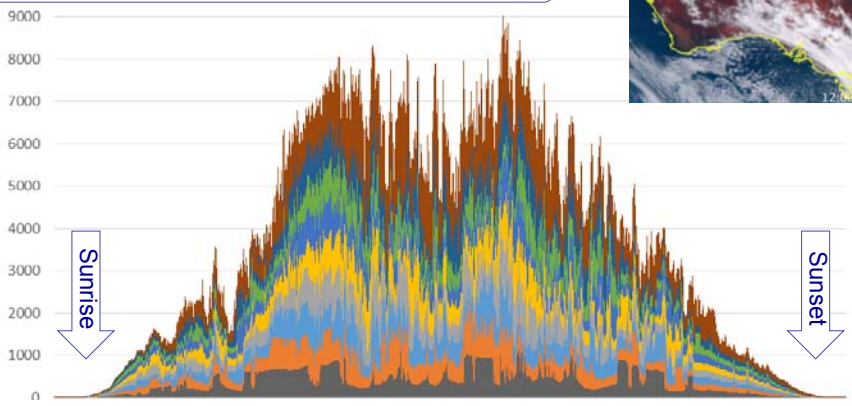
Figure 8. Imported (positive) and exported (negative) power from and into neighboring countries (based on Ref. [17]).

Solar flux at 9 Alice Springs sites on 11/9/13, cloudy & windy (CAT Projects, March 2015, Investigating the Impact of Solar Variability on Grid Stability)

http://arena.gov.au/files/2015/03/150302-Impact-of-Variability-Report-for-public-release.pdf



High resolution cloud map for 12 noon 14/1/16 from new Japanese satellite http://himawari8.nict.go.jp

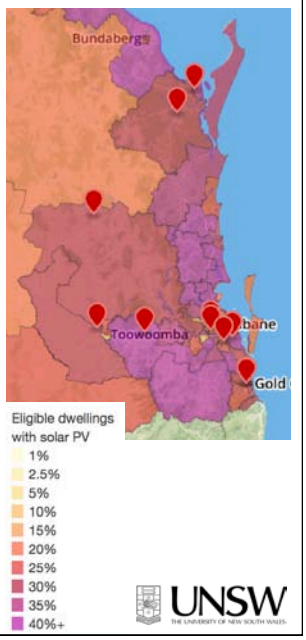


No solar flux at night & second to multi-week variability due to cloud behaviour; seasonal variability depends on latitude & climate; solar eclipses possible.
A strong network can exploit diversity between stochastic outputs of PV systems

Installed PV in Australia by State/Territory at 22/3/16

http://pv-map.apvi.org.au/historical#6/-30.297/144.536

Total PV GW at 22/3/16
Australia: 5 GW
NEM jurisdictions: 4.4 GW



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Estimated potential & penetration rates for commercial & residential rooftop PV in Australia, Warwick Johnston, 26/4/16

http://onestepoffthegrid.com.au/why-cost-commercial-pv-sales-dont-proceed-and-what-to-do-about-it/

State	Current Commercial Rooftop Capacity (MW)	Estimated Commercial Rooftop Available Capacity (MW) (ACIL ALLEN)	Commercial Penetration Rate	Residential Penetration Rate (Suitable Dwellings)
ACT	6	75	8%	20%
NSW	184	1,175	16%	23%
NT	9	42	21%	22%
QLD	93	772	12%	51%
SA	84	243	35%	48%
TAS	10	141	7%	20%
VIC	99	1,141	9%	22%
WA	57	528	11%	39%
National	**543**	**4117**	**13%**	**32%**

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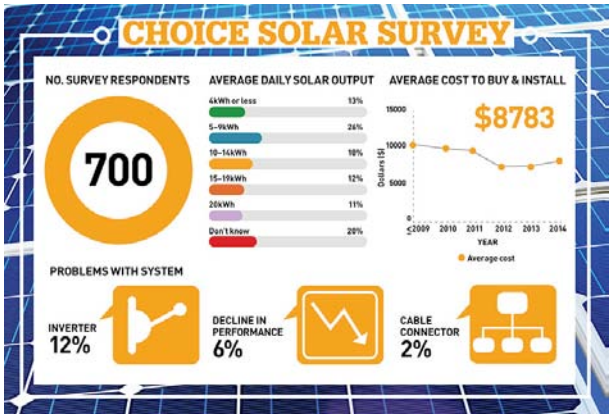
https://www.choice.com.au/home-improvement/energy-saving/solar/articles/solar-power-survey-results



AEMO, 2015 National Electricity Forecasting Report, Detailed Summary, June

Table 5 Proportion of rooftop PV relative to residential and commercial underlying consumption

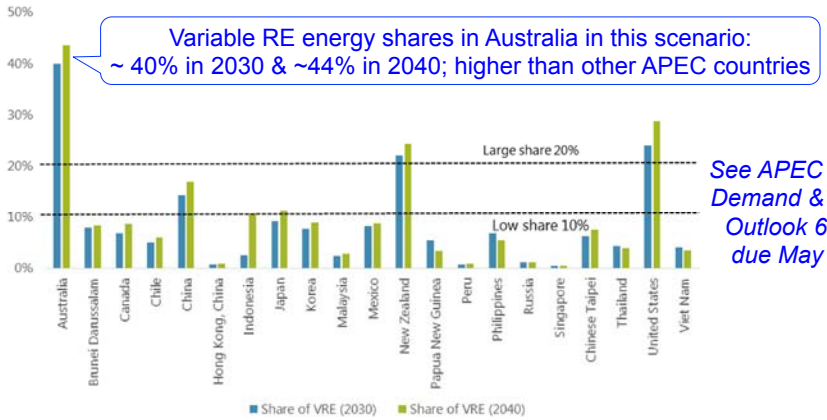
	Queensland	New South Wales	South Australia	Victoria	Tasmania
2014–15	5.7%	2.4%	8.4%	2.7%	3.0%
2017–18	9.1%	3.7%	11.9%	4.4%	4.9%
2024–25	16.0%	6.3%	22.1%	8.6%	11.0%
2034–35	20.2%	9.3%	28.5%	13.7%	17.4%

High renewable electricity generation scenario for APEC

Tam, APERC, 15/12/15

http://aperc.ieej.or.jp/file/2015/12/22/2-4_Alternative+Scenarios.pdf

Variable renewable integration



See APEC Energy Demand & Supply Outlook 6th Edn due May 2016

Variable renewables remain below 10% in most economies

APERC *Asia Pacific Energy Research Centre* 13

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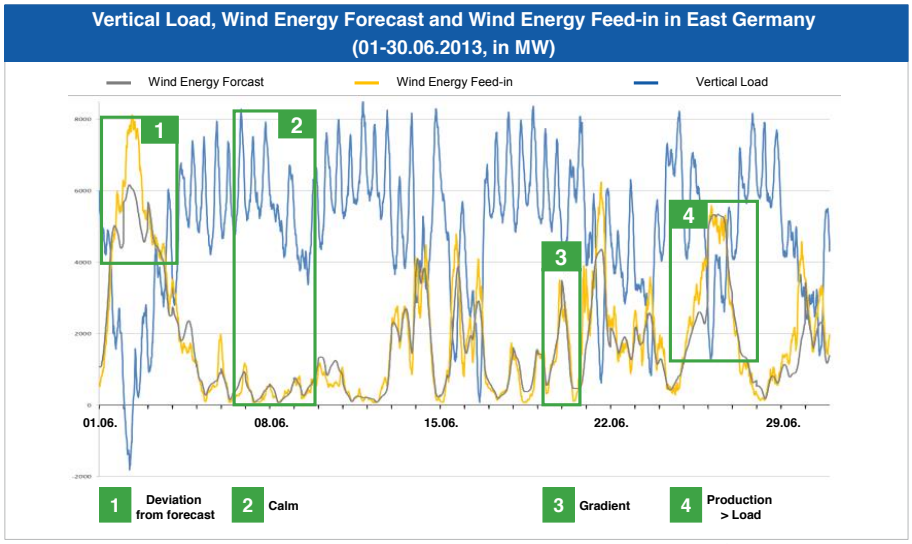
Load, wind energy & wind forecast in East Germany, June 2013
(Weinmann, Energy Storage World Forum, 28/4/15)



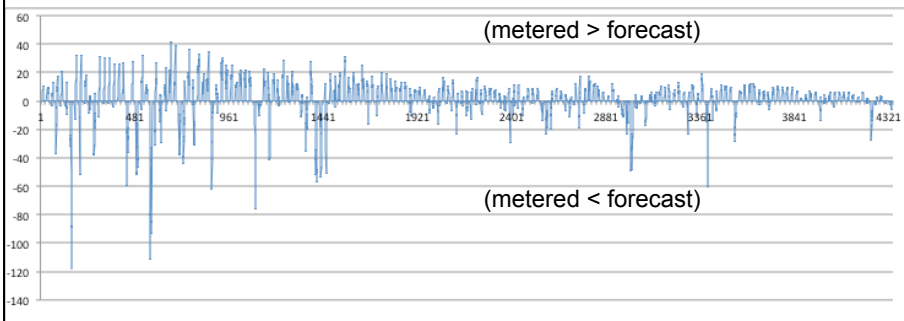
Source: 50Hertz Transmission

Energy Storage World Forum

VATTENFALL

CAISO day-ahead hourly solar generation forecast error, 1/1/14-30/6/14: (metered-forecast)/metered (%)

http://www.caiso.com/Pages/documentsbygroup.aspx?GroupID=0AD10C95-54E0-4BA2-89D0-DC88FBE9EFF0



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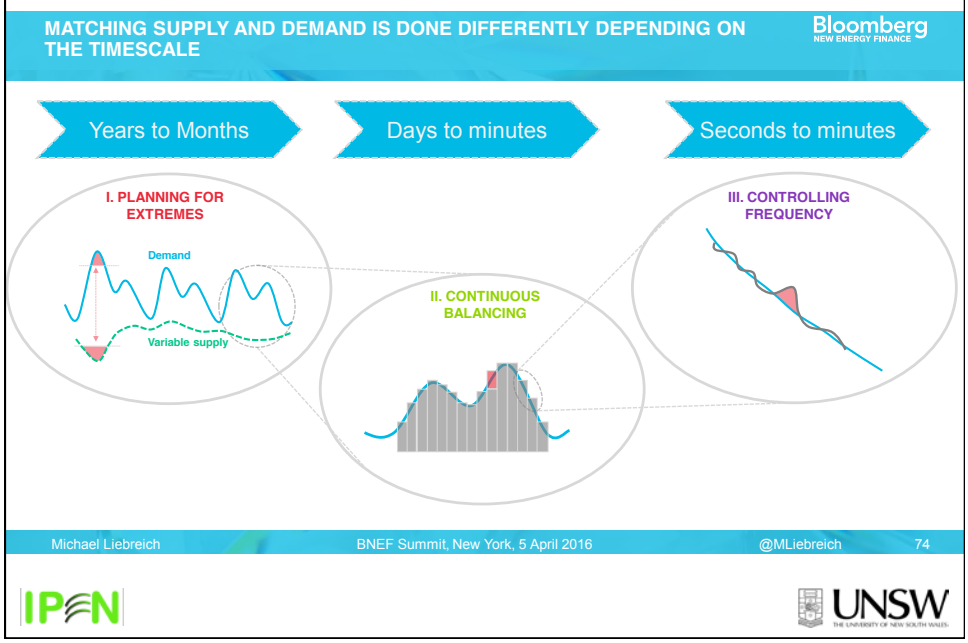
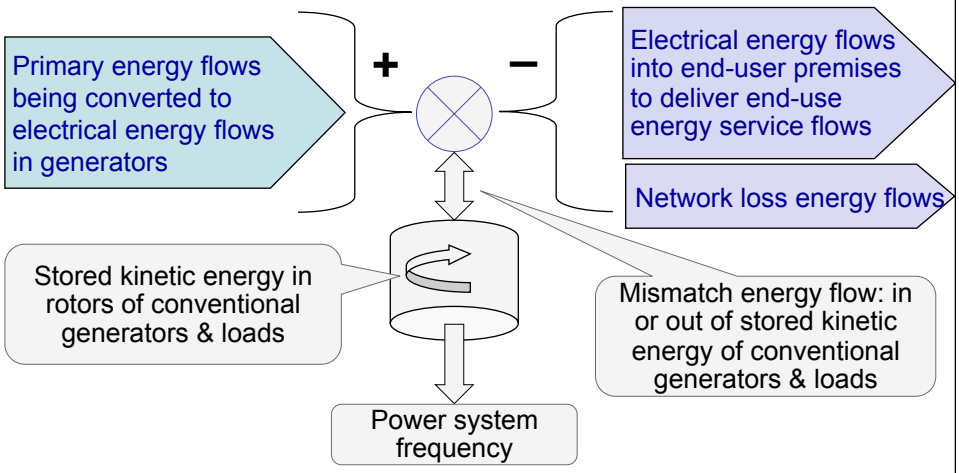
Michael Liebreich, *In search of the Miraculous,* BNEF Summit, New York, 5 April 2016, http://about.bnef.com/content/uploads/sites/4/2016/04/BNEF-Summit-Keynote-2016.pdf



Short-term energy flow balance in an electricity industry with conventional generators & loads



- Power system frequency reflects industry-level supply-demand balance:
  - Occasional large variations due to *contingencies*
  - Continuing small variations due to *diversified (generator-load) energy flow*
- *Converter-interfaced generators, energy stores & loads have no inertia*

(AEMO, Renewable Energy Roadshow, August 2015, www.aemo.com.au)

- **Develop a systematic / comprehensive approach to studying the operating limits of the power system as the generation mix changes**
- **Develop comprehensive range of technical issues associated with managing a power system with little or no synchronous generation**
- **Develop the analysis tools and models to analyse performance of a power system with little or no synchronous generation**

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Plan to address changing generation mix in SA & broader NEM

AEMO & Electranet, Update To Renewable Energy Integration In South Australia, Feb '16

Figure 5 Program overview

Adapt AEMO's functions and processes to deliver ongoing power system security and reliability

	Short-term 3-year outlook	Long-term 10-year outlook
Objective	Transparency and clarity in how AEMO intends to meet its obligations for system security and reliability as the generation mix changes.	To identify, rank and promote resolution where appropriate of long-term technical challenges of operating the power system to inform the need for policy, procedural or regulatory changes.
Approach	Initially focussed on South Australia as the region likely to first experience challenges, then considered NEM-wide focus. Review of procedures for operational management of the power system for a range of operating conditions including system normal, credible and non-credible contingencies by testing operational limits and identifying potential challenges. Where issues are identified, development of modified strategies within the current regulatory framework if necessary.	Consult with industry technical experts to identify and prioritise technical challenges. Research, modelling and analysis to confirm the nature and timing of any power system risks. Promotion of regulatory change with appropriate agencies where appropriate.
Outcomes	Clear operational strategies for the next three years with procedures in place for any identified risks.	Prioritised list of issues, and recommendations for progressing their resolution through changes to policy, regulatory, rules, procedural, technical or other mechanisms as appropriate.

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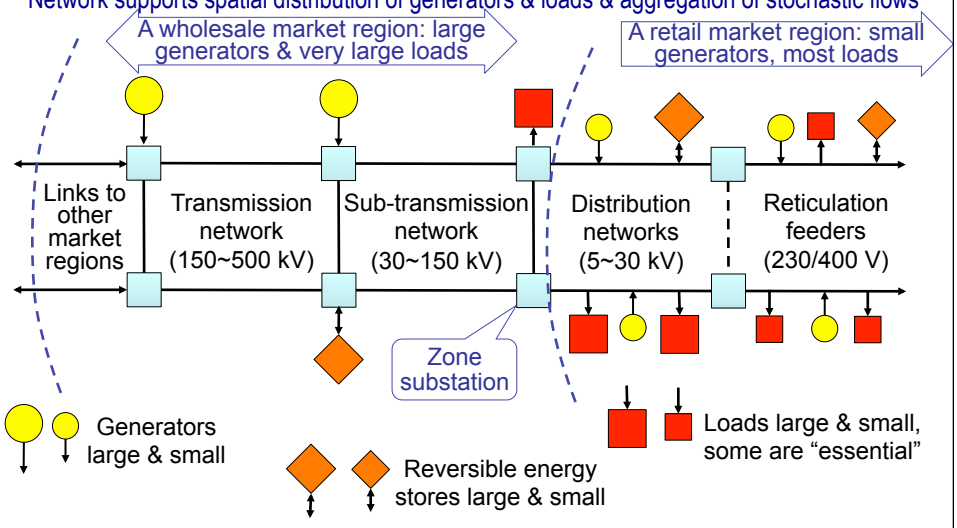
Electricity industry spatial structure & characteristics

Network supports spatial distribution of generators & loads & aggregation of stochastic flows



- *Merged AC electric energy flows through the network at speed of light & no intrinsic storage. The network is best viewed as a **common-pool resource***
- *Quality & rate of network energy flows must be continuously managed*
- *Large generators in wholesale market, small gens & most load in retail market*
- ***Wholesale/retail market separation not tenable with high wind, PV & store***

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SCHOOL OF ELECTRICAL ENGINEERING AND COMPUTER SCIENCE

DEPARTMENT OF ELECTRIC POWER ENGINEERING

REPORT DEPE 87.132

Welfare Maximizing Prices Under Uncertainty

R. John Kaye & Hugh R. Outhred

School of Electrical Engineering and Computer Science
University of New South Wales
Kensington, Australia

October 1987
Revised: January 1988

Abstract: This paper presents a new result in the theory of optimal pricing for public utilities or regulated monopolies. The derivation is based on a detailed model of consumers and suppliers which represents uncertainty and inter-temporal linking effects such as investment and storage. Thus the time evolution of the industry is accounted for. The optimal pricing structure would cause individual profit maximizing responses to be welfare maximizing. It contains two terms: Short Run Marginal Cost (SRMC) pricing as well as a new "incentive term" to account for the interaction of participants at different time points. A probabilistic forecast of pricing structures at future times is also required.

http://ipenconsulting.com/yahoo_site_admin/assets/docs/198801_WelfareMaxPricingKayeOuthred.113191834.pdf

"…all models are wrong but some are useful" George EP Box (1987)
Markets alone, e.g "Power Of Choice" are not enough

Key properties of *efficient pricing policies under uncertainty:*

- Apply symmetrically to buyers & sellers, support efficient decisions with inter-temporal links, such as storage or investment; guide network pricing
- *The efficient pricing policy* for a participant is ex-ante SRMC *plus* an incentive term exposing it to the effect of its decisions on the future profits of all participants *plus* probabilistic forecasting of future policies.
- *The efficient pricing policy* depends on quantity information & evolves. It can be implemented via spot & derivative markets for energy or price/quantity contracts for network access. *A predetermined price, e.g. LRMC, is wrong*
- The incentive term is negligible for small participants in context (price takers)

Some publications that expand on Report DEPE 87.132:

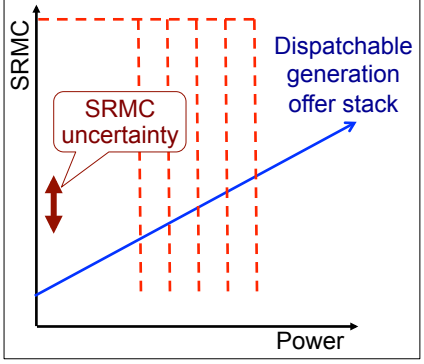
- Kaye and Outhred (1989), A theory of electricity tariff design for optimal operation and investment, IEEE Trans. Power Systems, Vol. 4, No. 2, pp 606-613, http://ieeexplore.ieee.org/xpl/tocresult.jsp?isnumber=5012
- Outhred et al (1988), Electricity pricing for optimal operation and investment by industrial consumers, Energy Policy, August, pp 384-393 http://www.sciencedirect.com/science/article/pii/0301421588901851
- Kaye, Outhred & Bannister (1990), Forward contracts for the operation of an electricity industry under spot pricing, IEEE Trans. Power Systems, Vol. 5, No. 1, pp 48-52, DOI: 10.1109/59.49085

SMRC discovery in a two-sided spot market

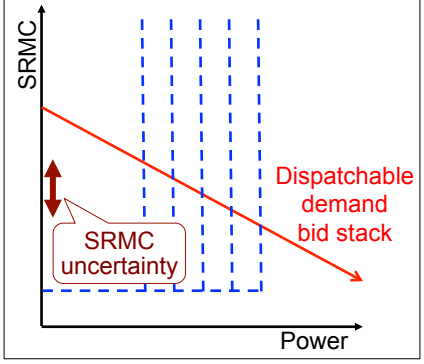
SRMC in a single-node, loss-less electricity industry is the least-cost way to meet a small increase in industry demand in the immediate future using a resource that is immediately available, and could be either:

1) A small increase in output by the marginal generator or discharging energy store, or
2) A small decrease in demand by the marginal end-user or charging energy store

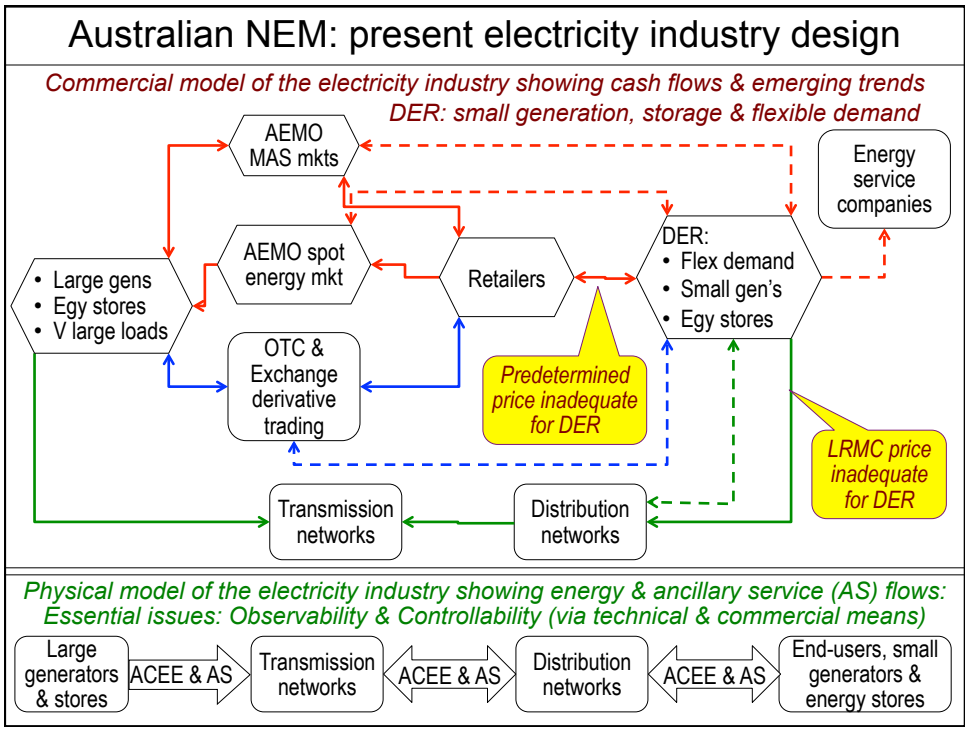
High value but uncertain demand:
supply offers critical in this case

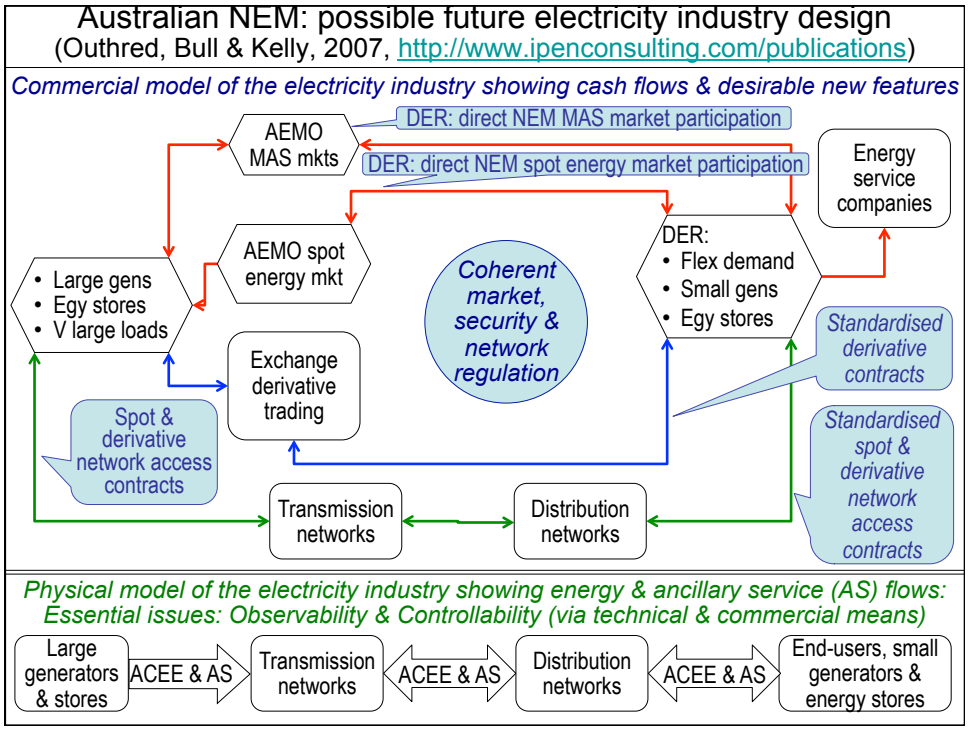


Low op. cost but uncertain supply:
demand bids critical in this case



Energy stores charge when SRMC low, discharge when SRMC high, subject to state of charge, cycle losses, etc. Need good forecasts & efficient derivative markets


Australian NEM: present electricity industry design
Commercial model of the electricity industry showing cash flows & emerging trends
DER: small generation, storage & flexible demand
AEMO MAS mkts
Energy service companies
AEMO spot energy mkt
Retailers
DER:
• Flex demand
• Small gen's
• Egy stores
• Large gens
• Egy stores
• V large loads
OTC & Exchange derivative trading
Predetermined price inadequate for DER
LRMC price inadequate for DER
Transmission networks
Distribution networks
Physical model of the electricity industry showing energy & ancillary service (AS) flows:
Essential issues: Observability & Controllability (via technical & commercial means)
Large generators & stores
ACEE & AS
Transmission networks
ACEE & AS
Distribution networks
ACEE & AS
End-users, small generators & energy stores


Australian NEM: possible future electricity industry design
(Outhred, Bull & Kelly, 2007, http://www.ipenconsulting.com/publications)
Commercial model of the electricity industry showing cash flows & desirable new features
DER: direct NEM MAS market participation
AEMO MAS mkts
DER: direct NEM spot energy market participation
Energy service companies
AEMO spot energy mkt
Coherent market, security & network regulation
DER:
• Flex demand
• Small gens
• Egy stores
• Large gens
• Egy stores
• V large loads
Standardised derivative contracts
Exchange derivative trading
Spot & derivative network access contracts
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End-users, small generators & energy stores

Conclusions

- Increasing wind, PV & storage penetration is having a disruptive effect on NEM design & operation:
  - Small generators, energy stores and flexible demand need to participate directly in NEM MAS, spot energy & derivative markets, with improved forecasting integration
  - Energy services companies should replace retailers
  - Network access contracts require a spot & derivative commercial/technical structure that contributes to managing flow quality, network constraints & investment
  - Ancillary services need ongoing review with respect to evolving technology, eg. converter interface generators
- Constraints on wind, PV &/or storage penetration may still be required in some circumstances

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Hugh Outhred Bsc, BE (Hons 1), PhD

Hugh Outhred is the Managing Director of Ipen Pty Ltd, which provides advisory and educational services on energy, society and the environment. He is also a Senior Visiting Fellow at the University of New South Wales, Sydney and Guru Besar Luar Biasa (Visiting Professor) at STTNAS Jogjakarta, Indonesia.

Hugh retired in 2007 after a 35-year career at the University of New South Wales, most recently as Presiding Director, Centre for Energy and Environmental Markets and Head, Electrical Energy Research Group, School of Electrical Engineering and Telecommunications.

Hugh has been a Fulbright Senior Fellow at the University of California Berkeley, a Member of the National Electricity Tribunal, a Member of the New South Wales Licence Compliance Advisory Board, a Board Member of the Australian Cooperative Research Centre for Renewable Energy, an Associate Director of UNSW's Centre for Photovoltaic Devices and Systems, a Member of CSIRO's Energy Flagship Advisory Committee and a Lead Author for the IPCC Special Report on Renewable Energy Sources & Climate Change Mitigation, 2012.

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