Optimisation and Game Theory for the Future Grid and Electricity Markets

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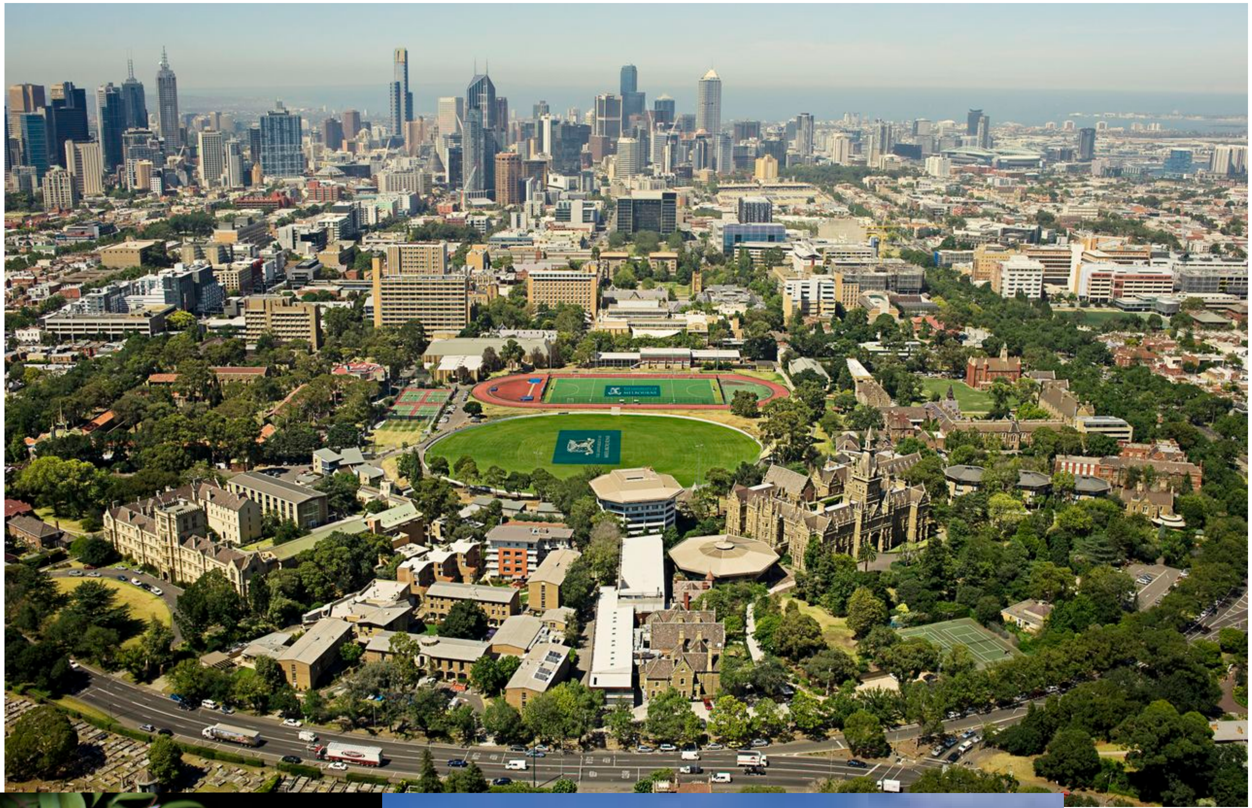
Outline

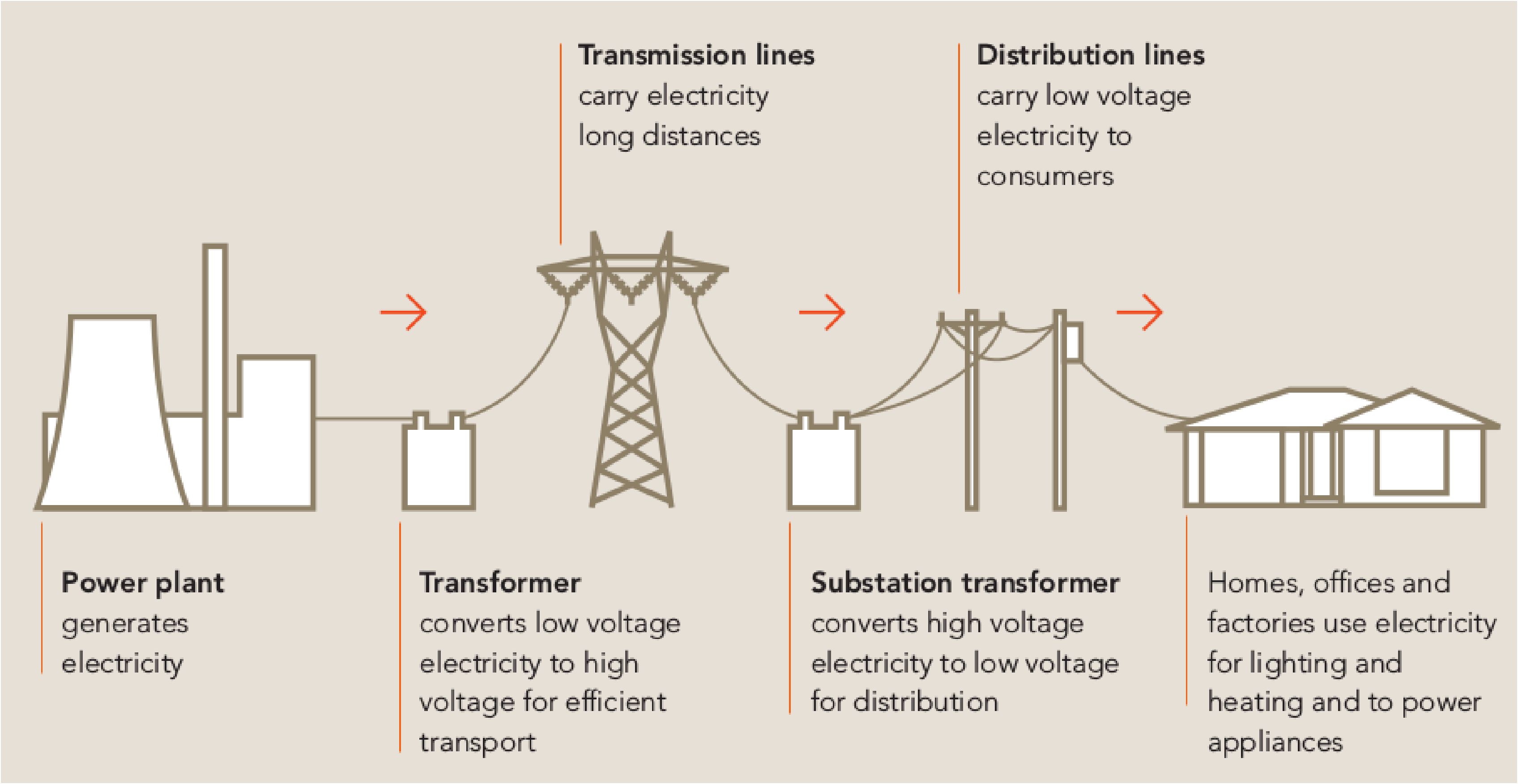
- Introduction
- Power Grid in Australia
- Modelling electricity markets using Game Theory
- Distributed Demand Management
- Optimal Charging of EVs



Power Grid and Renewable Energy Debate in Australia

Transformation of Power Grid

- Classic power grid is changing – the legacy system that is over 100 year old is under pressure in 21st century.
- Many aging coal plants in AUS reach end of their lives.



Transformation of Power Grid

Environmental concerns, less dependence on fossil fuels.

New technologies drive innovations:

Distributed and renewable generation (solar, wind).

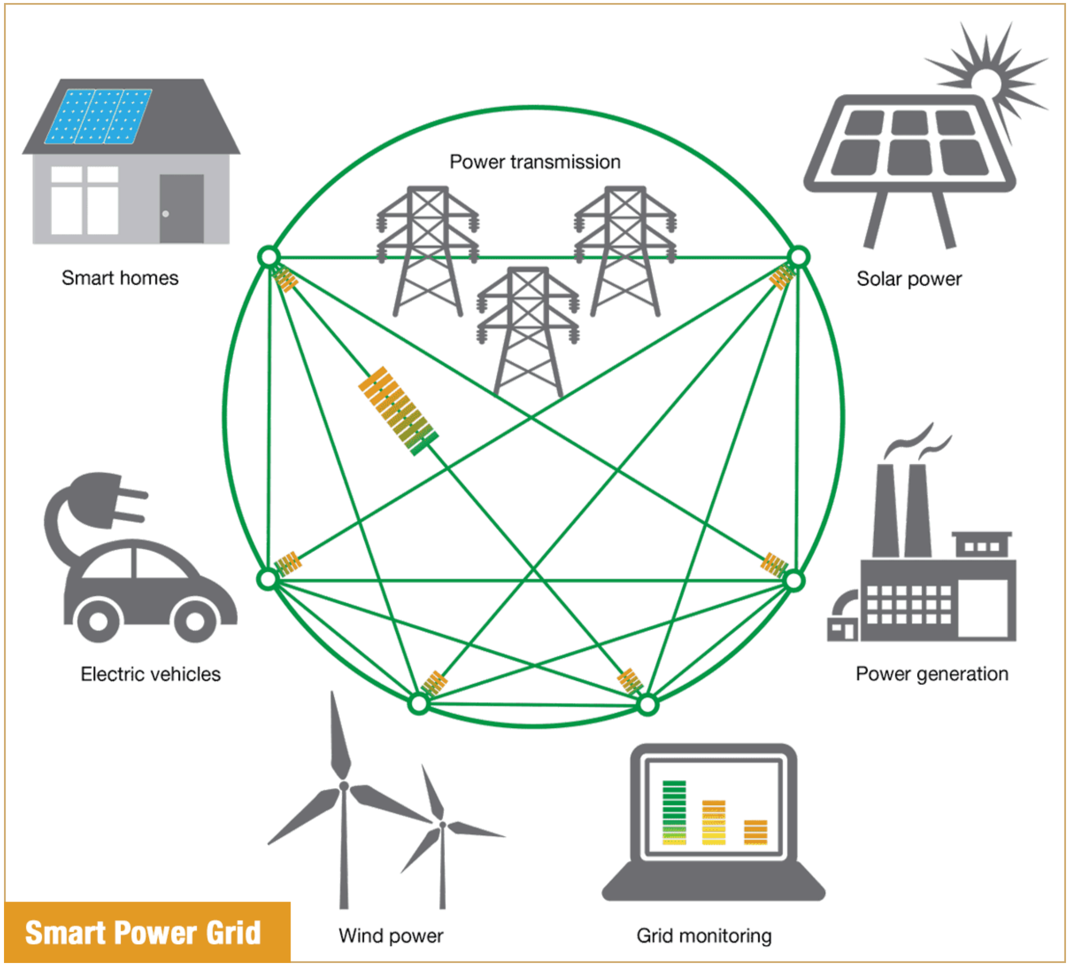
New type of loads: **EV**s

Demand management

(Battery) **Storage**

ICT in grid operations

Electricity **markets** (local and wholesale)



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Power Grid and Generation in Australia

BREAKDOWN OF CHARGES IN DOMESTIC ELECTRICITY BILLS, 2015–16[18]

Wholesale and retail	42%
Network costs	50%
Environmental policies	8%

2106
turbines in 79 wind farms across Australia

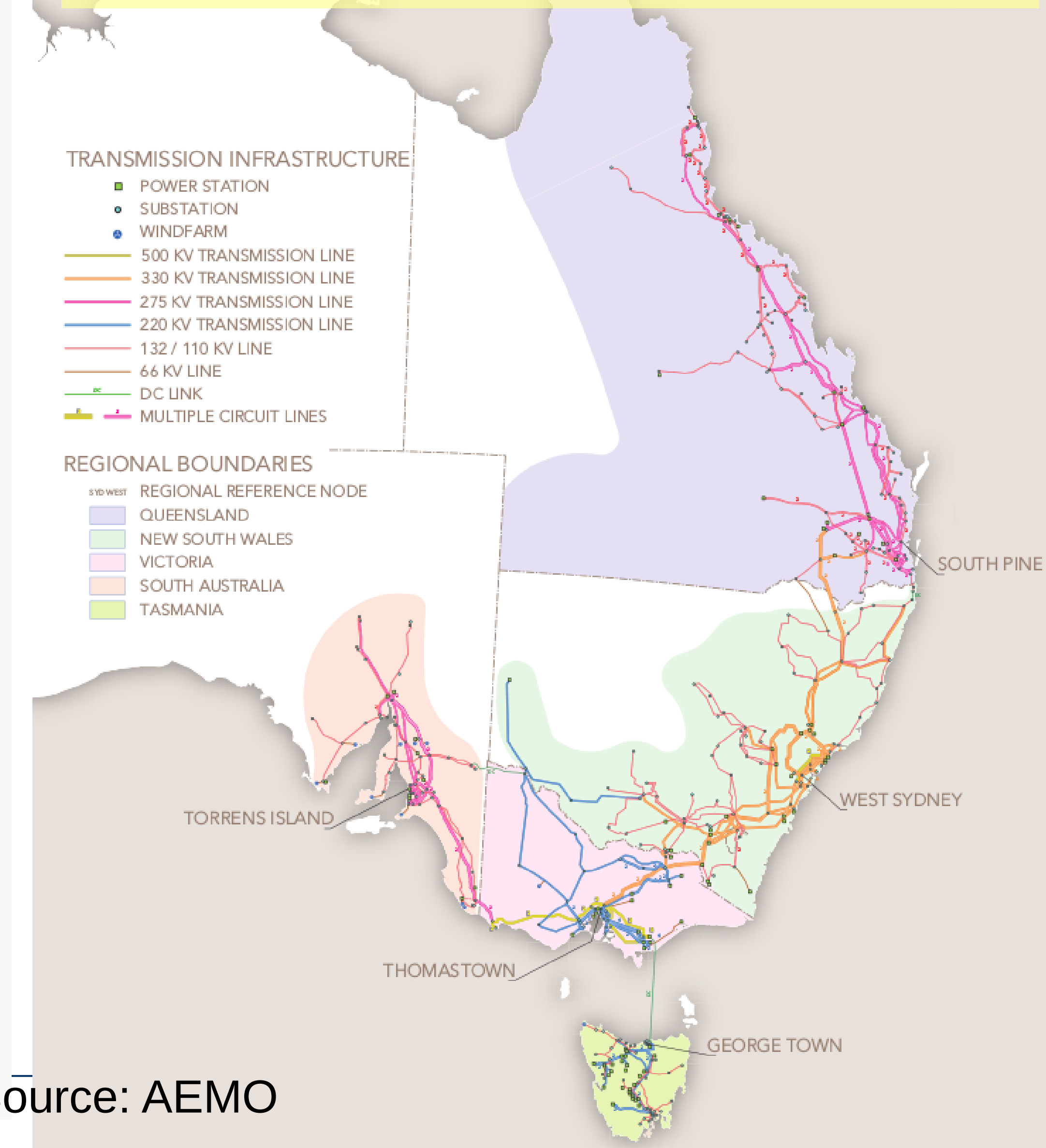
4327
megawatts of generating capacity

ANNUAL GENERATION BY FUEL TYPE (2014/15):

Share	Generation	Fuel type
100%	193,968 GWh	
50%	97,199 GWh	BLACK COAL
26%	51,118 GWh	BROWN COAL
12%	23,050 GWh	GAS
7%	12,662 GWh	WATER
5%	9,406 GWh	WIND
0%	533 GWh	OTHER

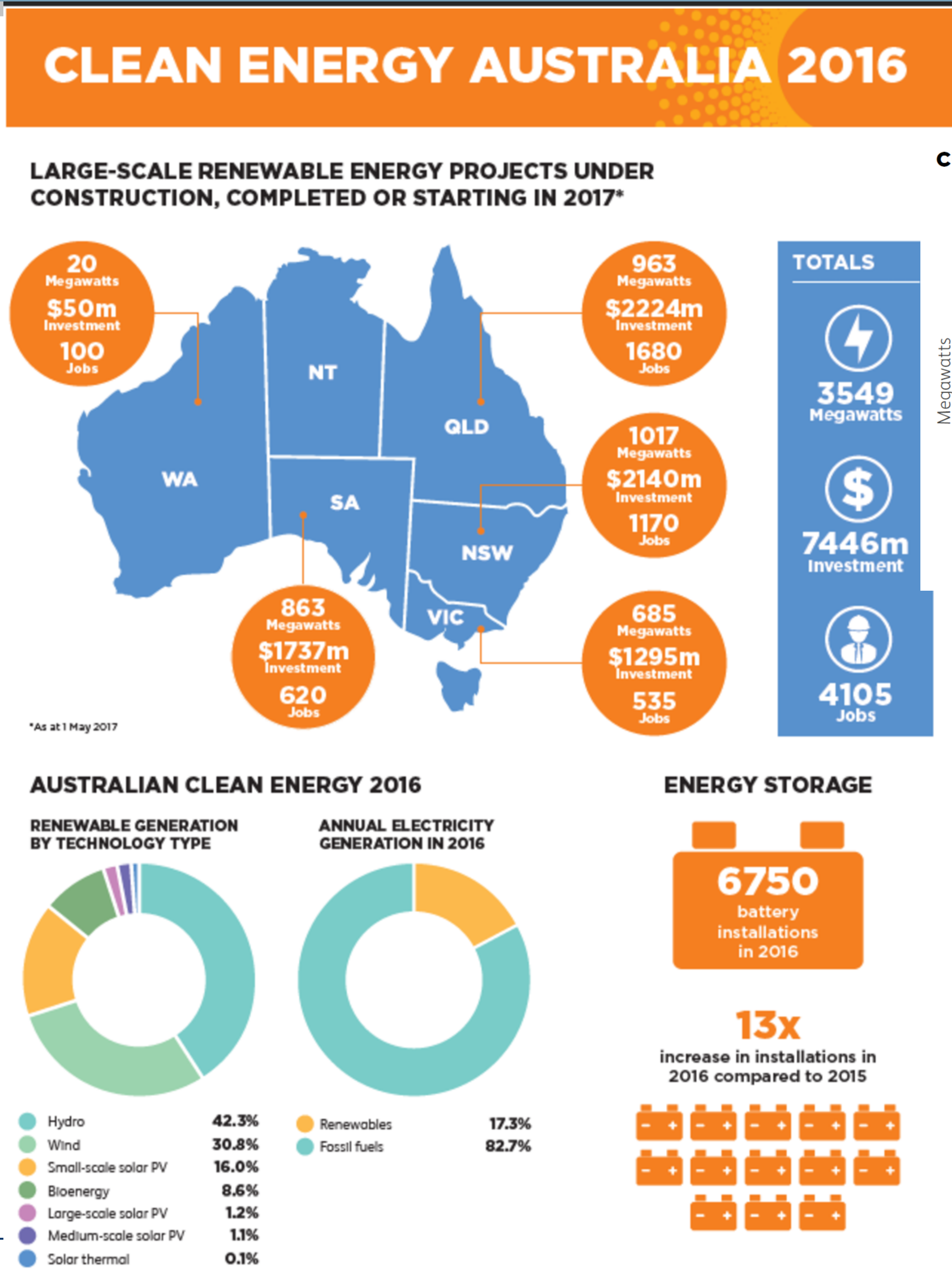
Data does not include generation from rooftop solar PV systems

NEM is overseen by **AEMO** (system operator) covers SA, VIC, TAS, NSW, QLD

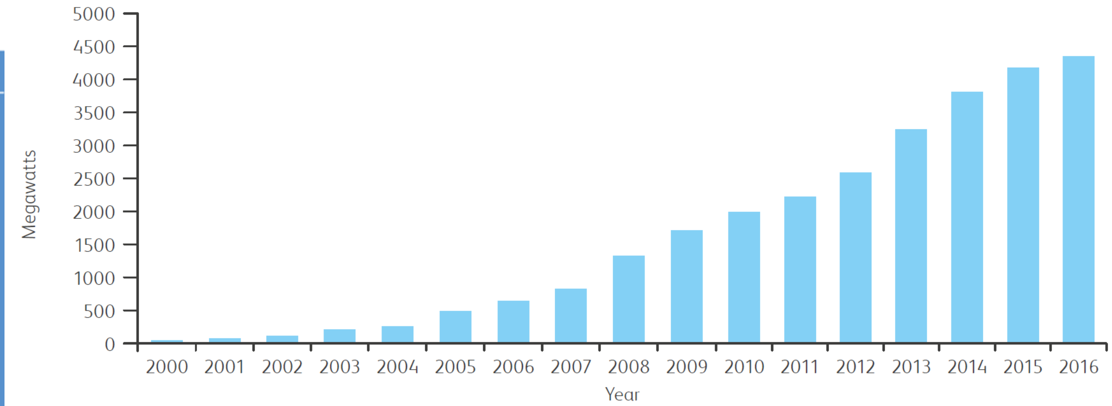


Source: AEMO

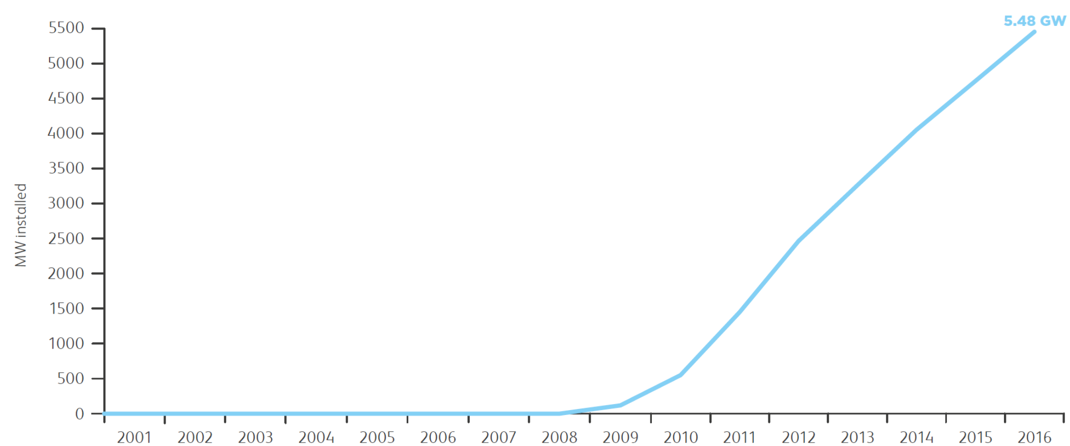
Renewable Energy in Australia



CUMULATIVE INSTALLED WIND CAPACITY IN AUSTRALIA



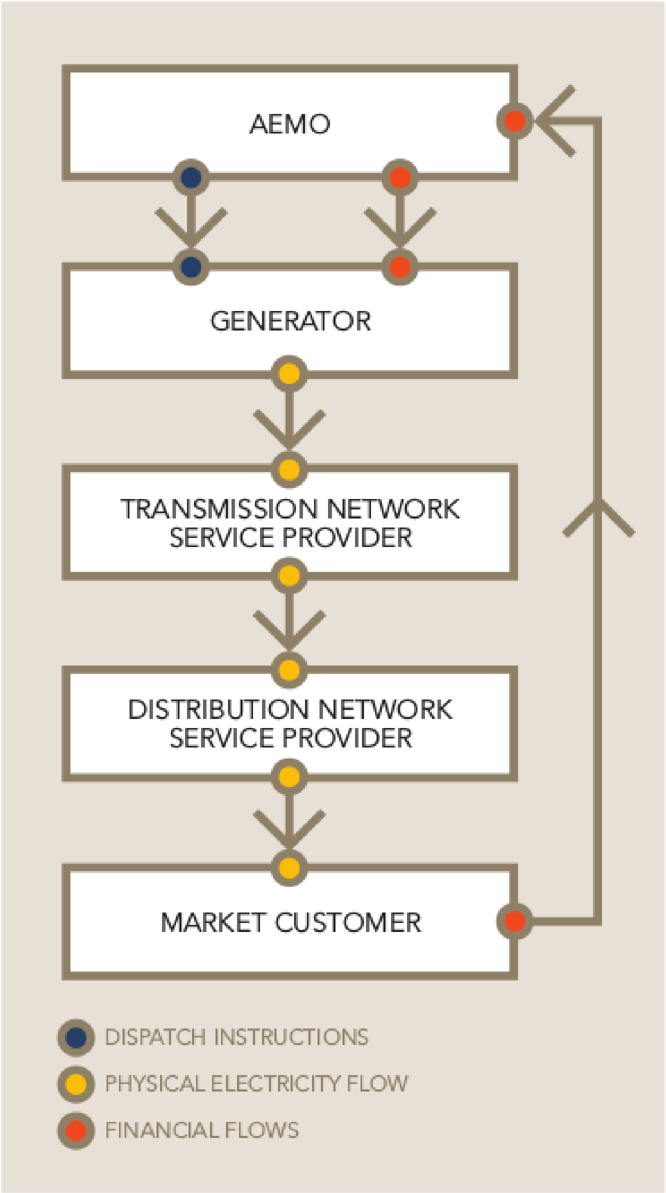
CUMULATIVE INSTALLED CAPACITY OF SOLAR PV IN AUSTRALIA (MW)[34]



Source: Clean Energy Council, AUS

Australian NEM

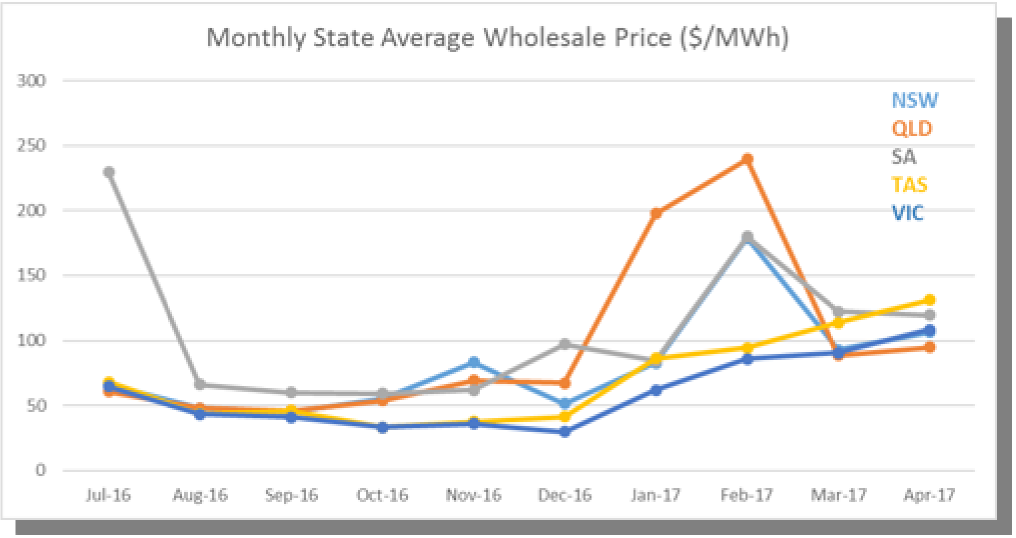
- The **Australian National Electricity Market (NEM)** is a wholesale market for the supply of electricity to retailers.
- Its operations today are based in five interconnected regions that largely follow state boundaries: SA, VIC, TAS, NSW, QLD.
- The NEM operates on the world's longest interconnected power system – around 5,000kms.
- Around AUD $7-8 billion of electricity is traded annually in the NEM to meet the demand of more than **nine million consumers**
- AEMO is the Power System and Market Operator.

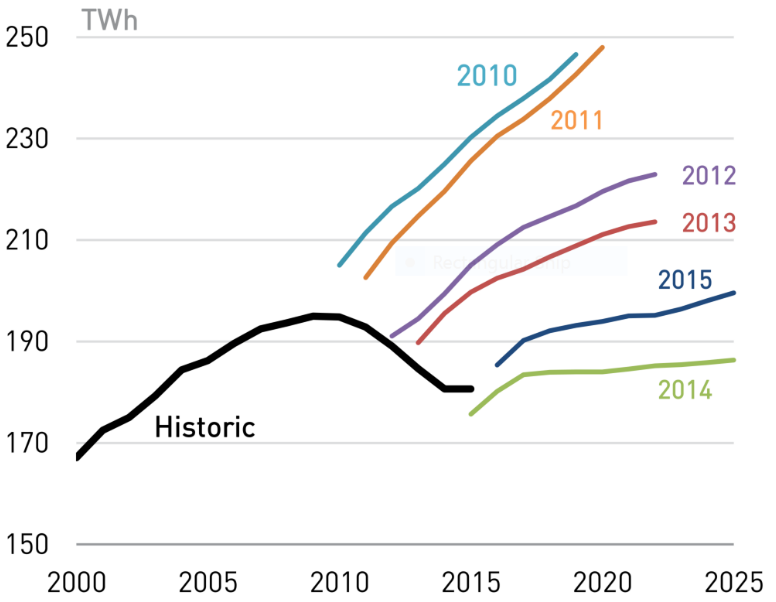


ENERGY AND FINANCIAL FLOWS

Issues in Australia

- Generators, distributors, and retailers - segmented
- Demand is correlated to weather (air conditioning!)
- Gold plated poles and wires, regulatory issues
- More recently:
  - Increasing gas prices affect wholesale prices
  - Retiring coal plants
  - Reliability problems in SA.





NEM prices (above, *AGL*) and consumption estimates (below, *reneweconomy*)

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Modelling Electricity Markets, NEM in Australia

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Game-Theoretic Model

- Each generator *i* solves the profit maximisation problem:

$$\max_{q_i \geq 0} U_i(q) = q_i P(q) - c_i q_i \quad \text{s.t.} \ Aq \leq b$$

- Market demand for electricity approximated as a linear function:

$$P(q) := \alpha - \beta \sum_i q_i \geq 0,$$

- Generation is modelled as a non-cooperative (**Cournot**) game. The Nash Equilibrium solution is obtained.

Our **recent publications** on wholesale markets using Cournot game models:

- A. Masoumzadeh, E. Nekouei, T. Alpcan, "**Impact of a Coal Power Plant Closure on a Multi-region Wholesale Electricity Market**," to be presented in IEEE ISGT Europe 2017.
- A. Masoumzadeh, E. Nekouei, T. Alpcan, D. Chattopadhyay, "**Impact of Optimal Storage Allocation on Price Volatility in Energy-only Electricity Markets**," IEEE Transactions on Power Systems (accepted)
- D. Chattopadhyay and T. Alpcan, "**Capacity and Energy-Only Markets under High Renewable Generation**," IEEE Transactions on Power Systems, vol. 31, no. 3, pp. 1692-1702, May 2016.
- E. Nekouei, T. Alpcan, and D. Chattopadhyay, "**Game-Theoretic Frameworks for Demand Response in Electricity Markets**," *IEEE Trans. on Smart Grid*, vol. 6, no. 2, pp. 748-758, March 2015.
- D. Chattopadhyay and T. Alpcan, "A Game-Theoretic Analysis of Wind Generation Variability on Electricity Markets," *IEEE Transactions on Power Systems*, vol. 29, no.5, pp. 2069 – 2077, September 2014.

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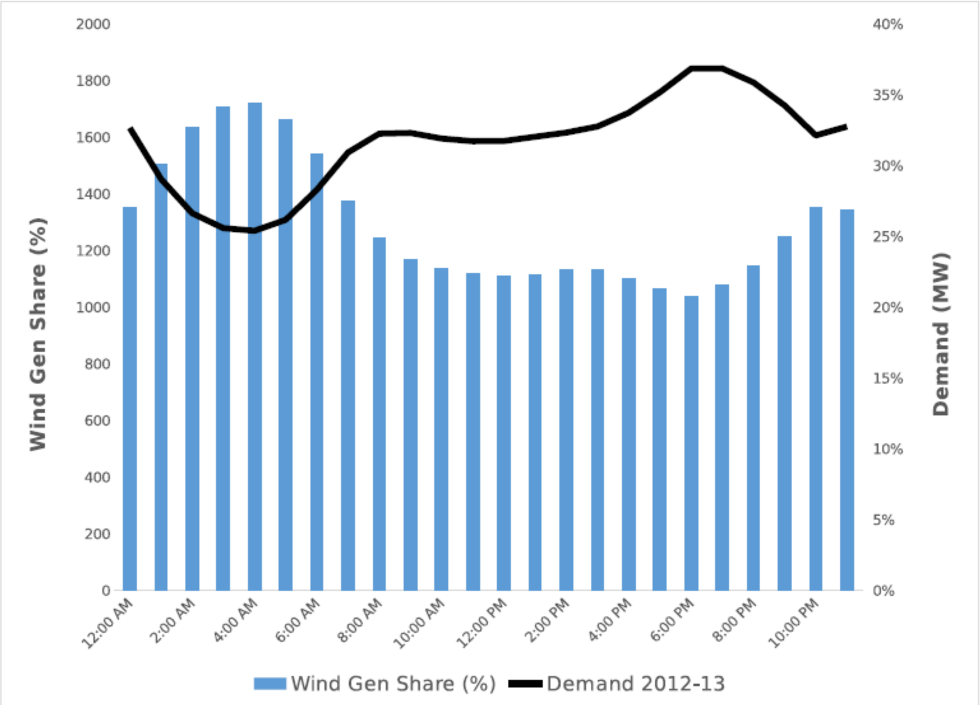
Capacity and Energy-Only Markets under High Renewable Generation

- **Multi-nodal Cournot gaming model with transmission constraints**.
- Simulate energy-only and capacity-energy market designs under intermittent renewable power generation.
- The model is applied to the **South Australia.**
- Results show that the capacity-energy market has the potential to induce significant new capacity and push prices much closer to the competitive level.

2017 development: SA government's intervention to NEM with state-owned new 250MW gas plant to be built.



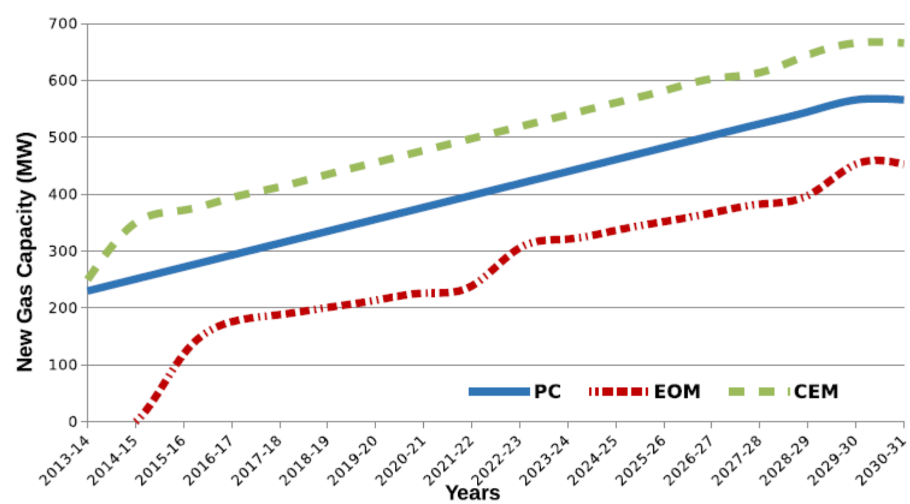
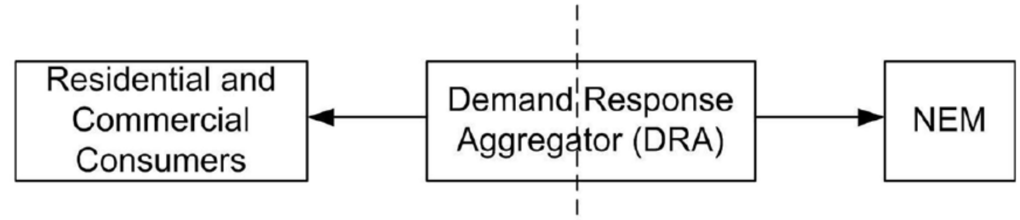
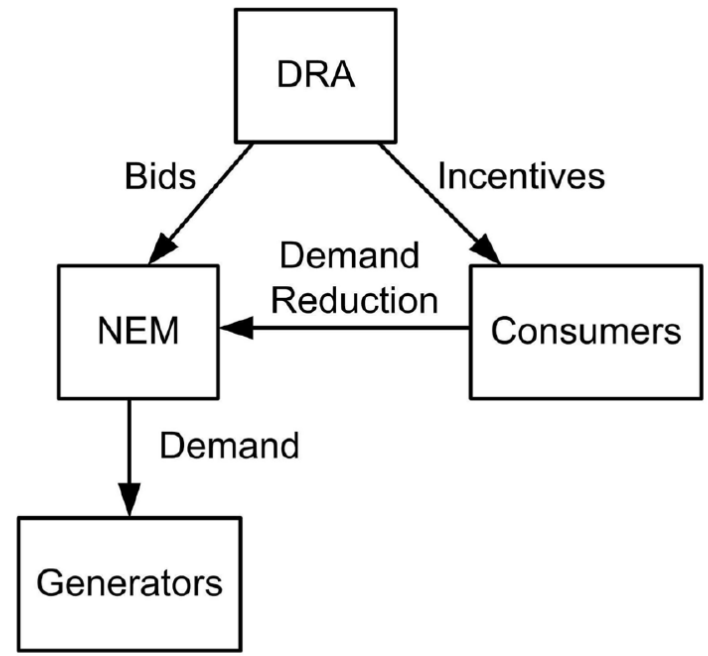


Fig. 8. Comparison of cumulative gas capacity entry (MW).

Game-Theoretic Frameworks for Demand Response in Electricity Markets

- Game-theoretic frameworks for **demand response** at both electricity market and consumer levels.
- DRA, as the leader of the game, makes demand reduction bids, and generators, as followers, compete for maximising their profits based on the reduced demand.
- The interaction between the DRA and consumers is modelled as a **mechanism design** problem.
- Case study: off-peak DR even in a concentrated market is not financially attractive.

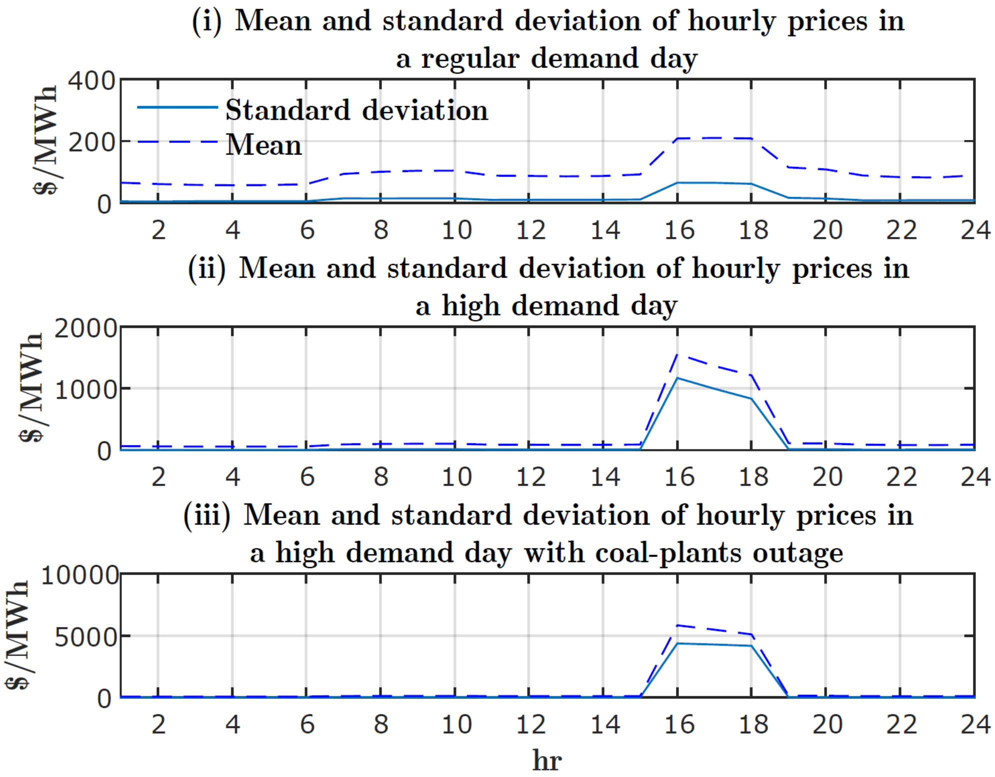




2017 development: AEMO and ARENA Demand Response project (100MW, $22.5M over 3 years)

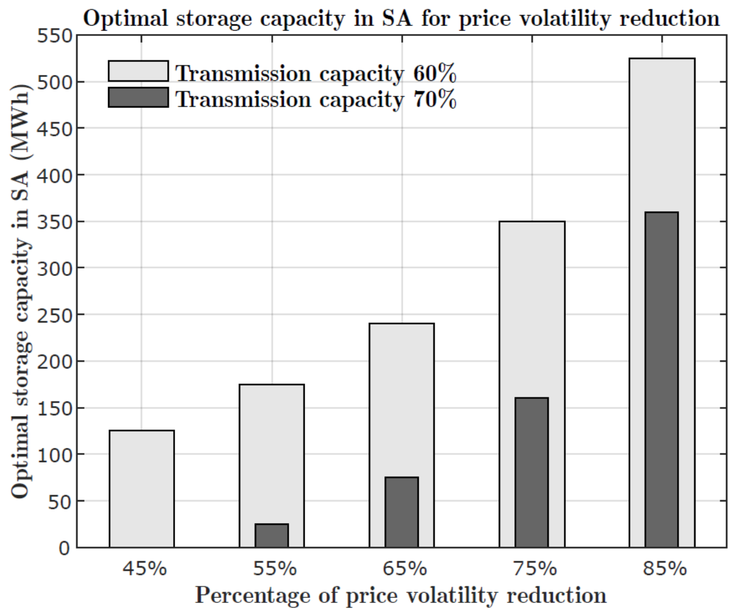
Impact of Optimal Storage Allocation on Price Volatility in Energy-only Electricity Markets

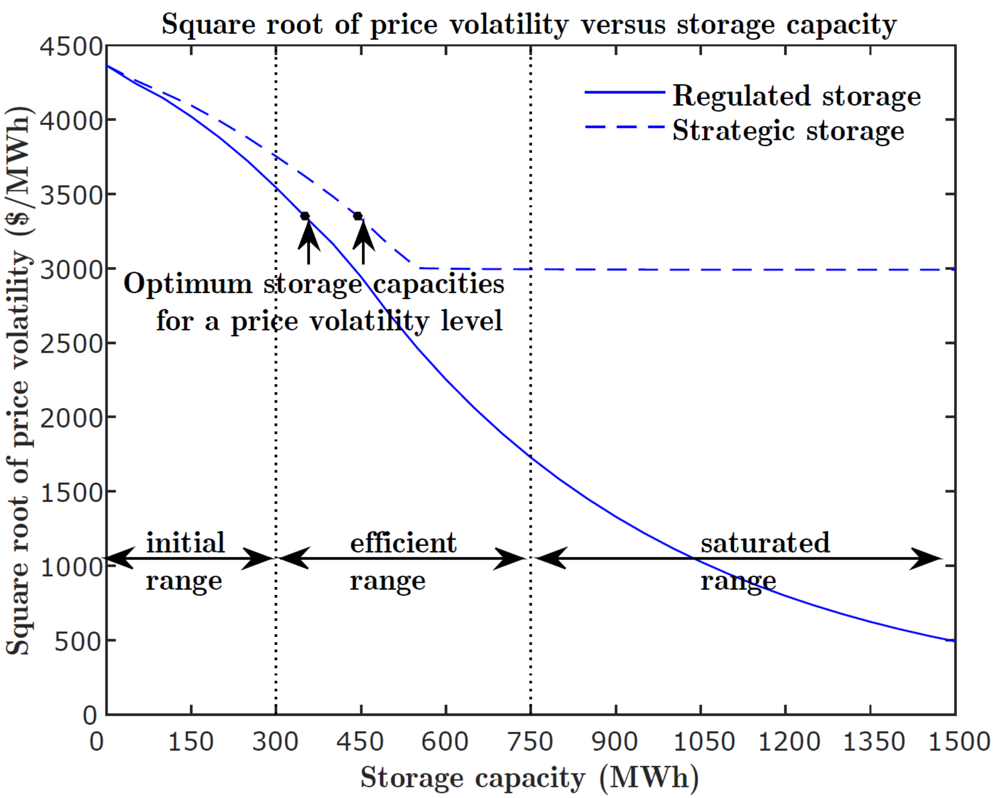
- **Storage can decrease extreme price volatility** due to its time-shifting, fast-ramping and price arbitrage capabilities
- A stochastic bi-level optimisation model is studied to find optimal nodal storage capacities required to achieve a certain price volatility level in a highly volatile energy-only electricity market.
- **Bi-level optimisation+game formulation.**
- The South Australia (SA) electricity market as the case study.
- Numerical results indicate that 50% price volatility reduction in SA electricity market can be achieved by installing either 430 MWh regulated storage or 530 MWh strategic storage.



Impact of Optimal Storage Allocation on Price Volatility in Energy-only Electricity Markets

- Storage alleviates but does not completely remove price volatility in the market due to the **wind intermittency**.
- The effect of a storage firm on price volatility reduction depends on whether the firm is regulated or strategic.
- Both storage devices and transmission lines are capable of reducing the price volatility.
- Intermittent wind power generation makes the region highly price volatile without classical generation capacity.





2017 development: SA government announced $150million for storage technologies in 2017.
Elon Musk has offered 100 to 300 MWH of grid battery capacity @ $250/kWh...

Impact of a Coal Power Plant Closure on a Multi-region Wholesale Electricity Market

- Closure of a base-load power plant may have a significant impact on wholesale markets.
- A **Cournot-based multiregion game model** based on nonlinear inverse demand functions analyzes the impacts of a base-load plant closure on the price level and volatility (increase), and CO2 emission (decrease).
- **Case study**: simulations of Hazelwood coal plant closure in Victoria, AUS, indicate around 30% and 49% price and volatility increase in the wholesale market, and 210 million AU$ (+3.5%) higher annual power bills in Victoria for final consumers.
- Market power of remaining players leads to wholesale price increases.

2017 development: Hazelwood coal plant (1600MW capacity) closes in first half of 2017.

Peak price distribution

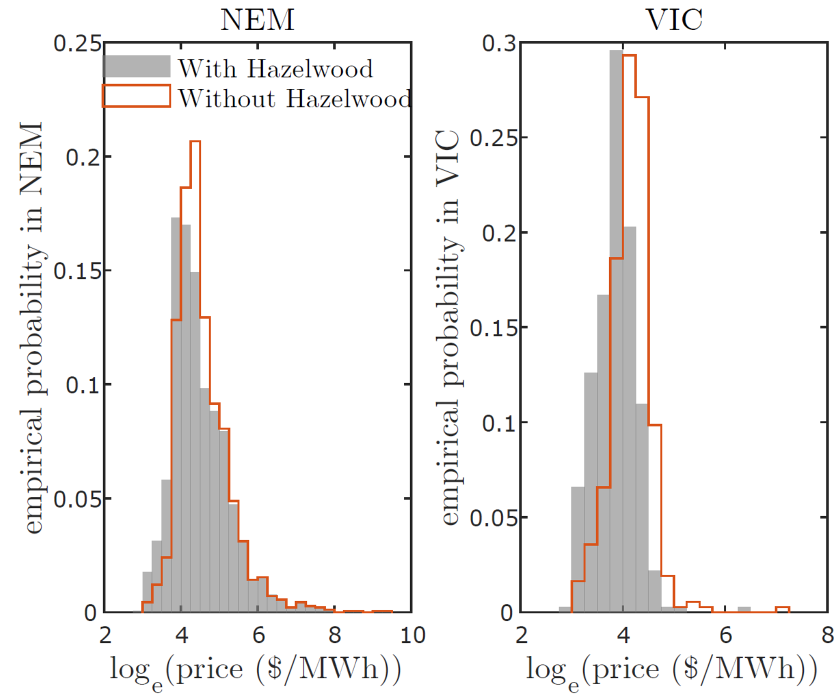


TABLE II: The annual electricity generation profit (billion$ per year) in five-node NEM market, considering the closure of coal power plant Hazelwood in VIC.

Profit (b$/year)	SA	QLD	TAS	**VIC**	NSW	NEM
before closure	0.38	1.55	0.32	**1.33**	1.08	4.68
after closure (change%)	0.38 (+2.2%)	1.55 (+0.0%)	0.36 (+9.9%)	**1.54 (+15.9%)**	1.11 (+2.9%)	4.96 (+6.1%)

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Distributed Demand Management

Distributed Demand Management

- *Local Measurements and Virtual Pricing Signals for Residential Demand Side Management* (DSM) on Distribution Grid.
  - DSM has the potential to reduce peak demand and improve grid utilisation.
  - Existing methods often require a bi-directional communication infrastructure.
- **Approach**: local voltage measurements and a distributed optimisation formulation.
- **Result**: distributed DSM with local measurements performs close to centralised solution.

Recent publications:

- J. de Hoog, T. Alpcan, M. Brazil, D. A. Thomas, I. Mareels, "**A Market Mechanism for Electric Vehicle Charging Under Network Constraints**," *IEEE Transactions on Smart Grid*, vol. 7, no. 2, pp. 827-836, March 2016.
- L. Xia, J. de Hoog, T. Alpcan, M. Brazil, D. A. Thomas, I. Mareels, "Local measurements and virtual pricing signals for residential demand side management," *Sustainable Energy, Grids and Networks*, vol. 4, pp. 62-71, December 2015.

Network Constraints

- Transformer capacity rating
- Line current rating
- Phase unbalance
- Voltage constraints

Note:

- all constraints are modelled as linear!
- DC approximation is used in the distribution network with high power factor

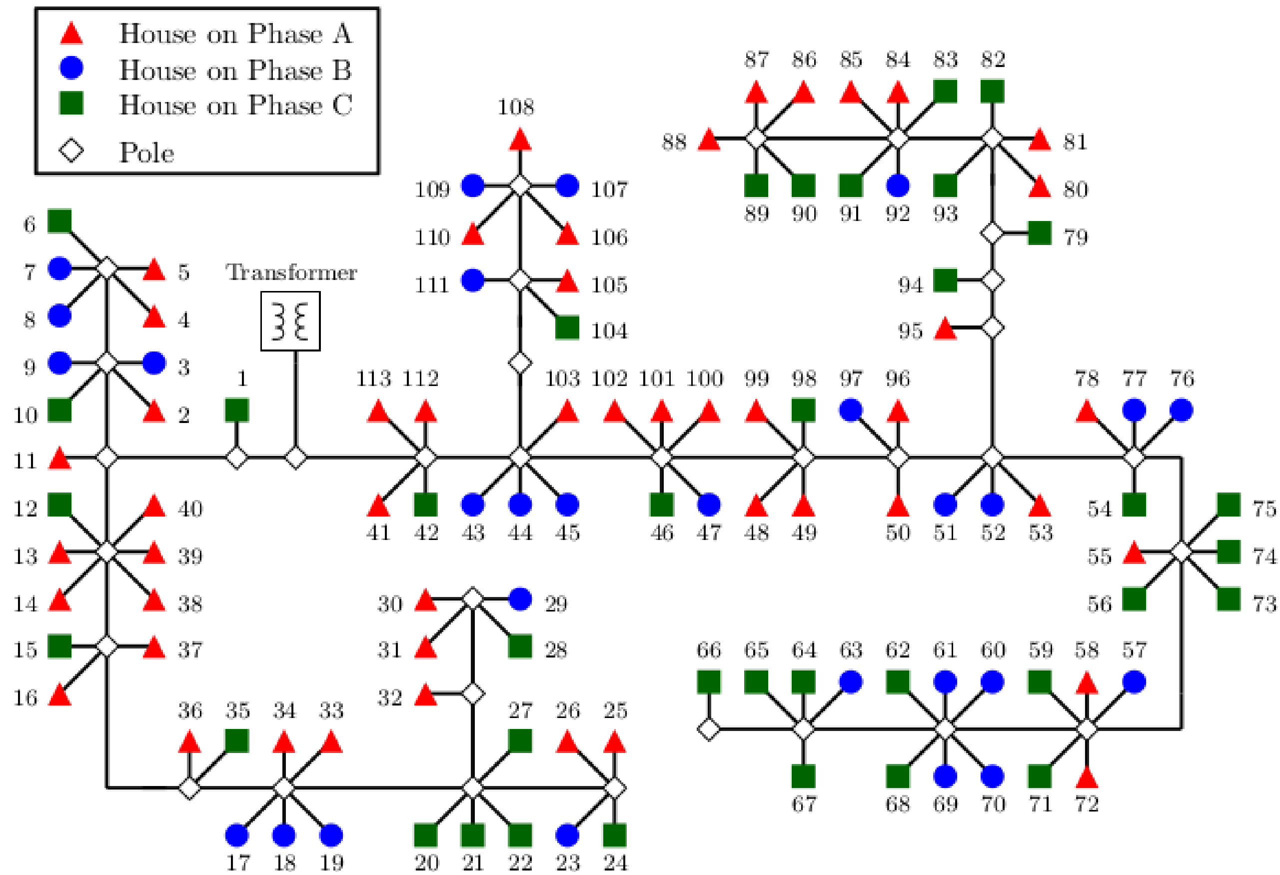

Diagram of an suburban distribution network in Melbourne, Australia of 113 houses.

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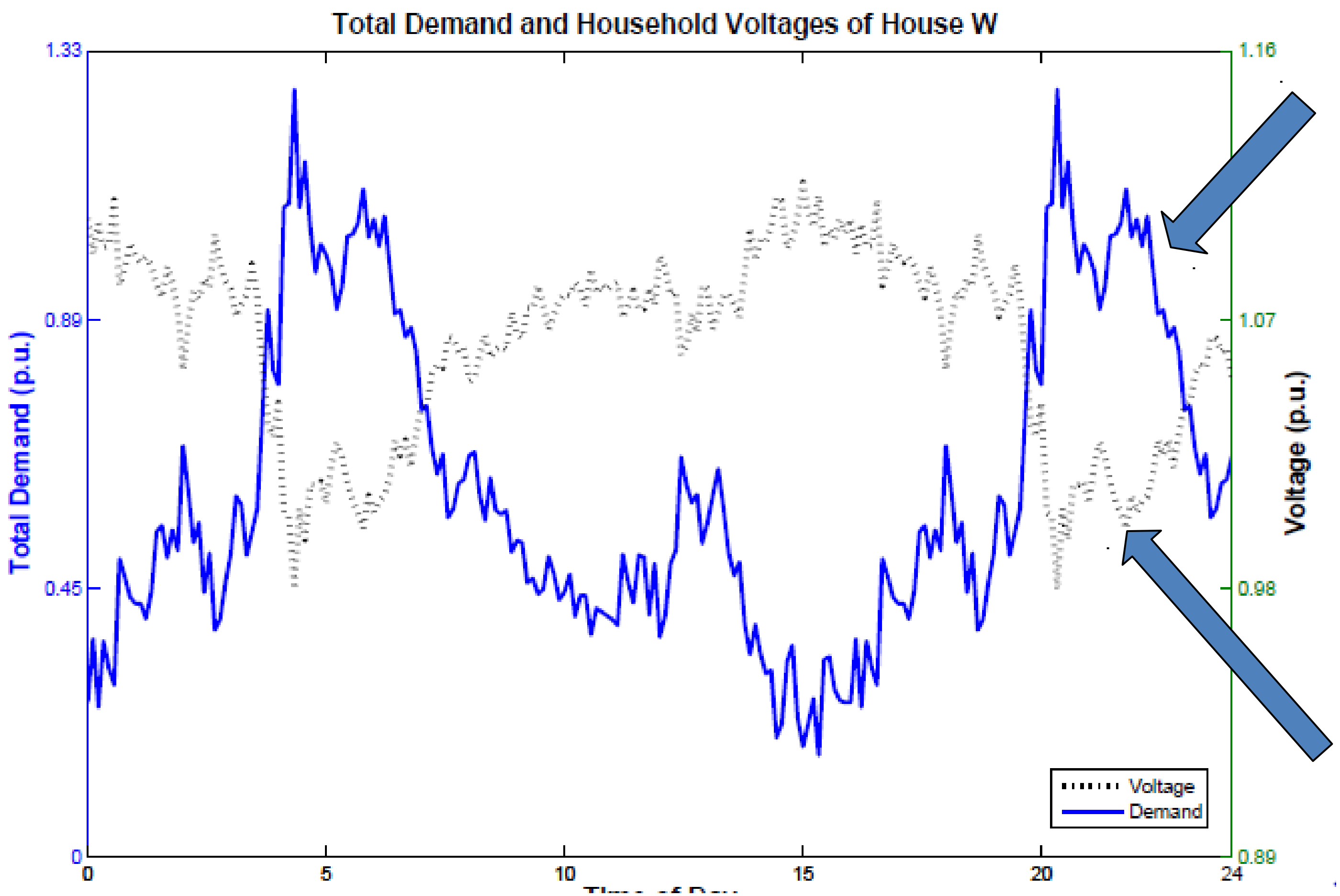
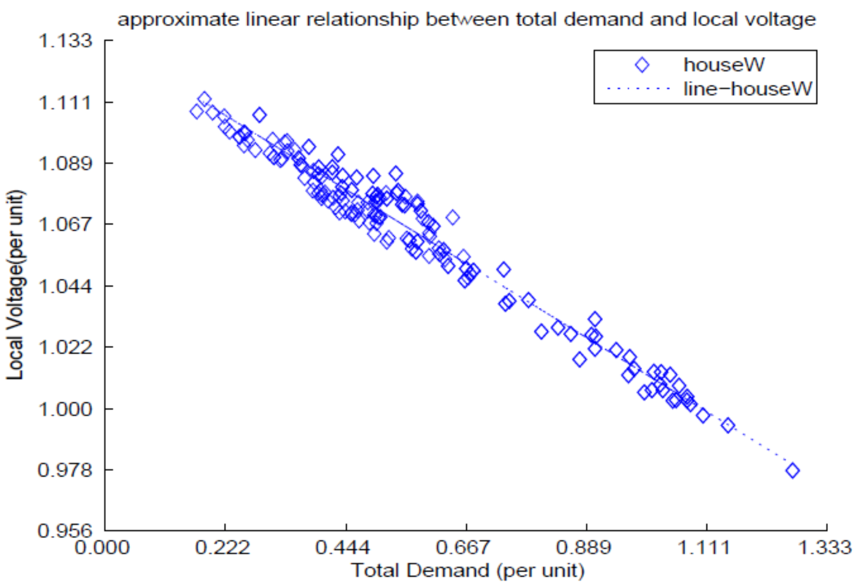
Local Voltage vs Local Demand

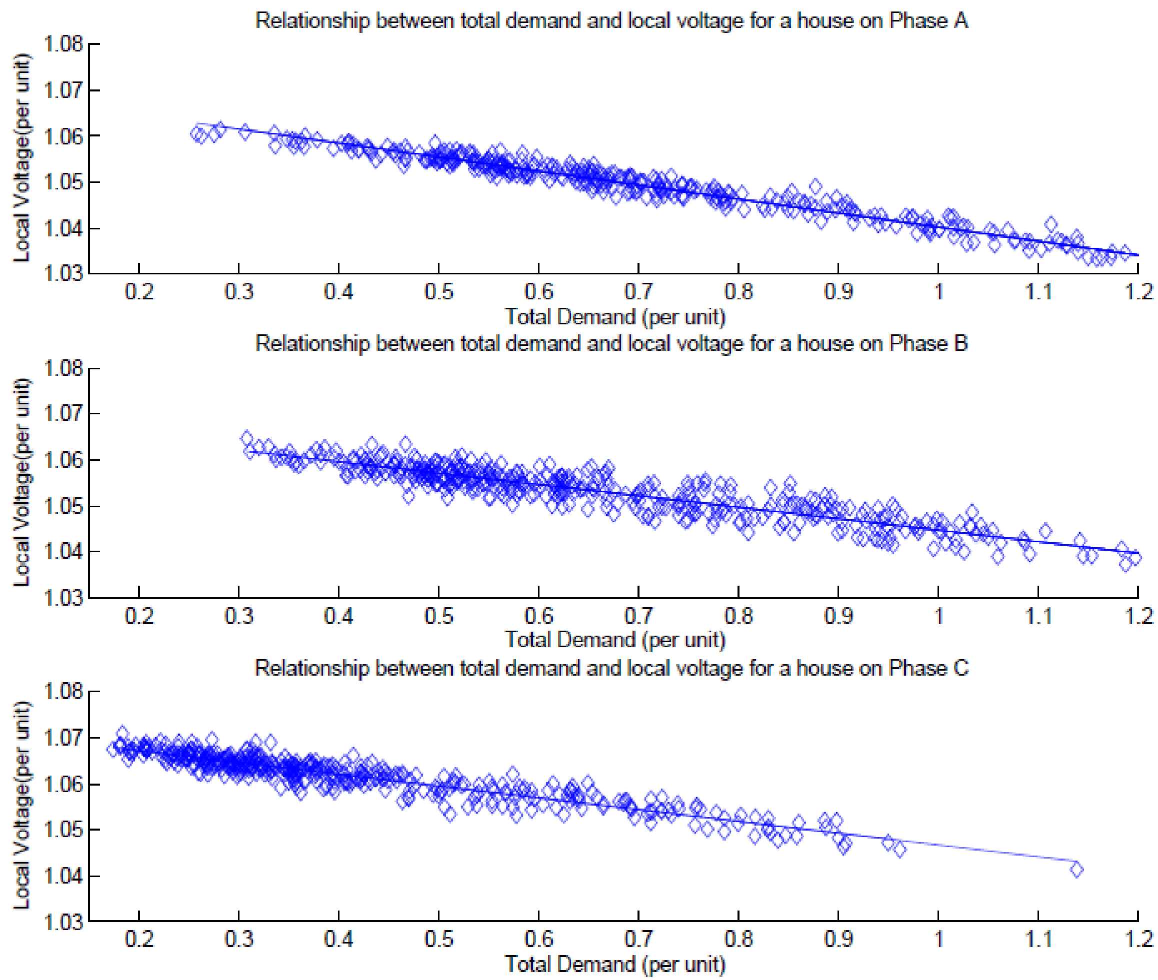
Local voltage measurements as demand indicator



Plot of local voltage for a typical household and network demand

Local Voltage vs Local Demand





The correlation can be seen as a result of projecting a low dimensional data that is embedded into a high dimensional space (each user/house a dimension)

Local Voltage vs Local Demand

Local voltage measurements as demand indicator
with local Solar PV generation

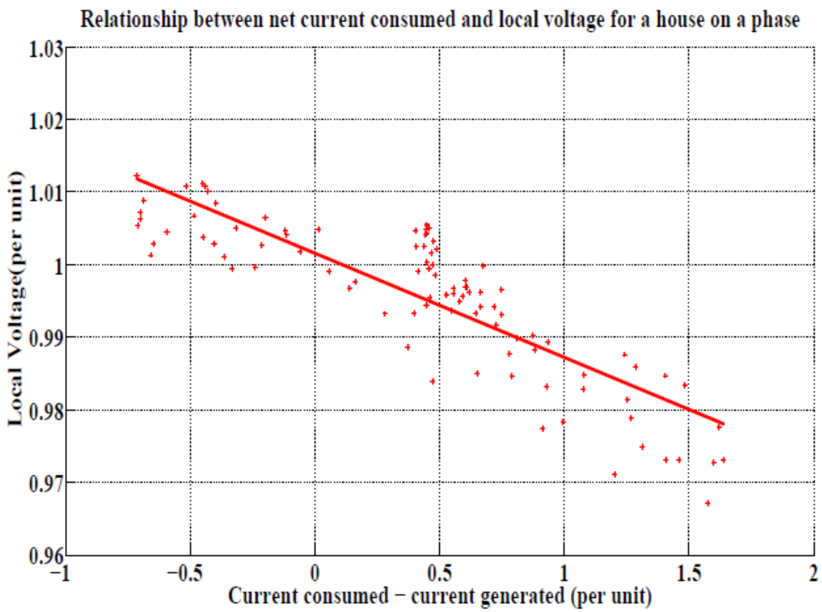


Figure 8. Relationship between network net current consumed and local voltage of a random house in the network. (30% penetration)

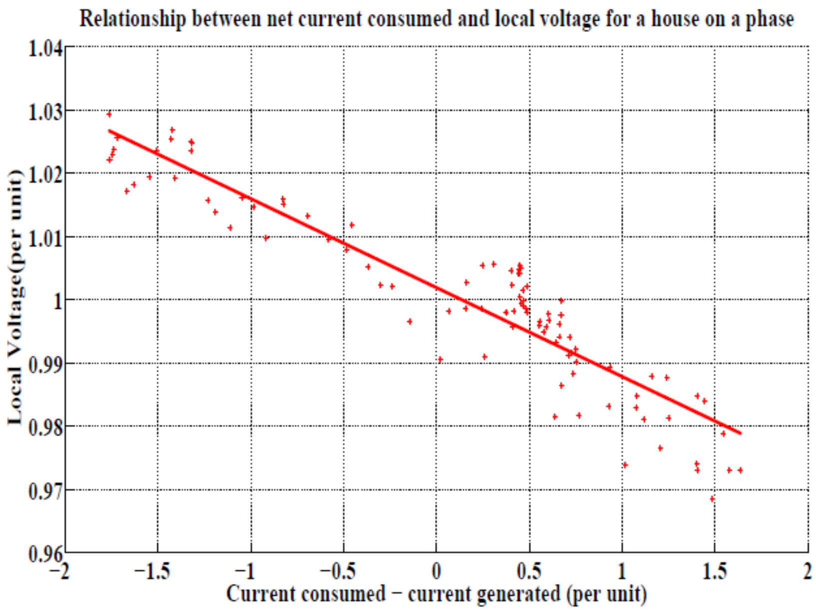
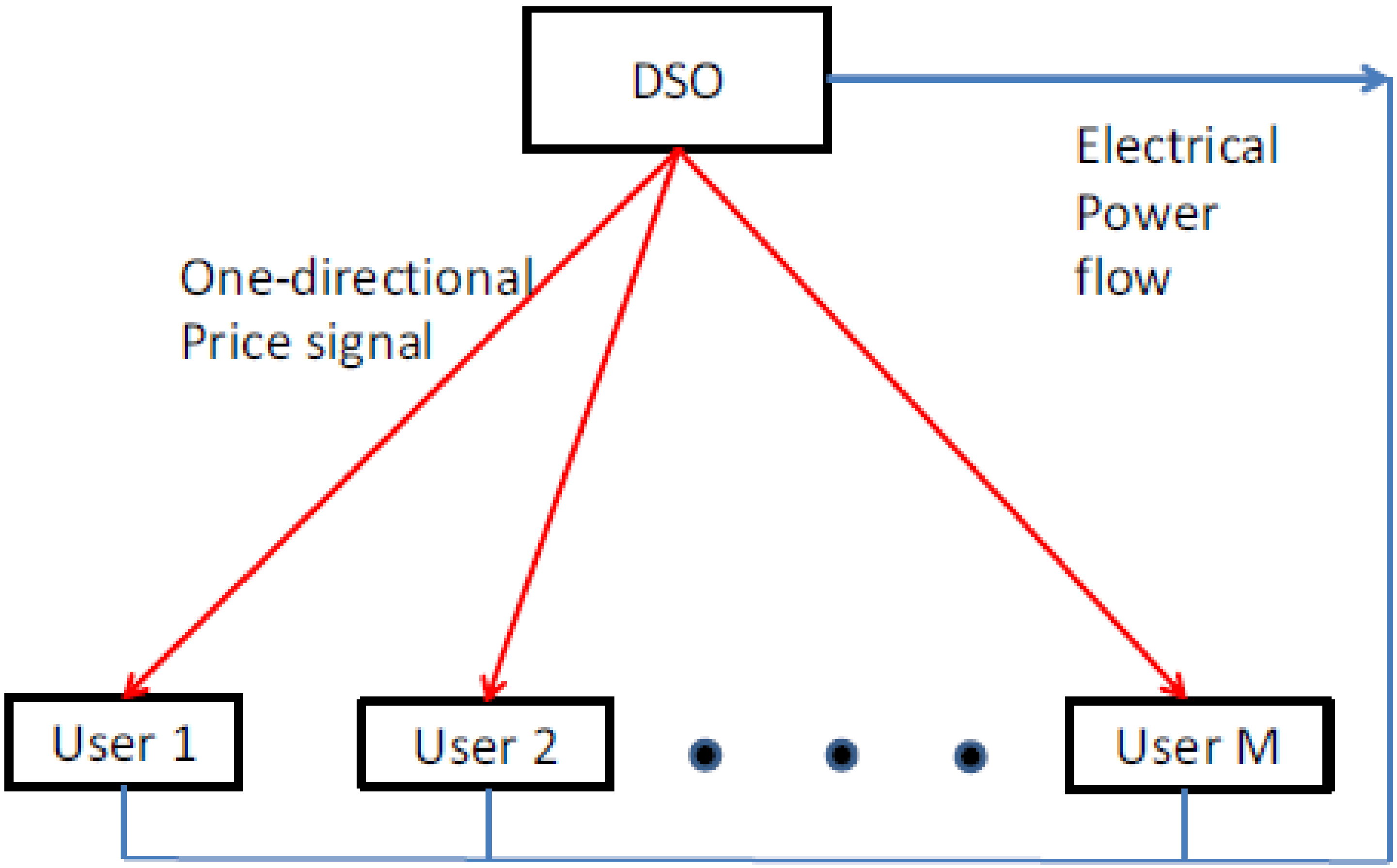


Figure 9. Relationship between network net current consumed and local voltage of a random house in the network. (50% penetration)

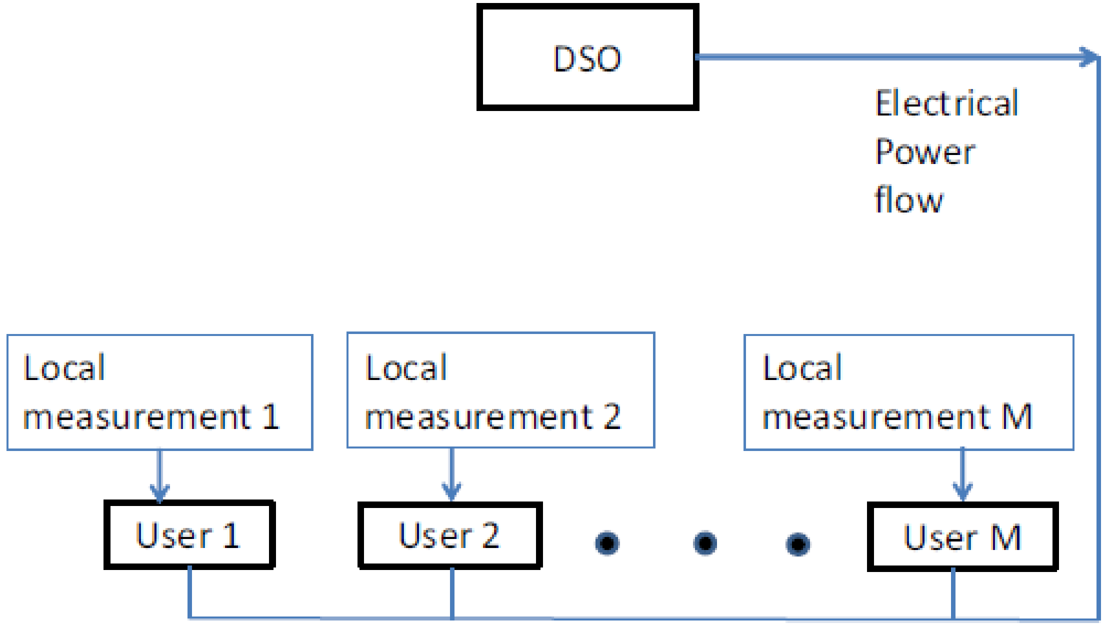
Local generation by Solar PVs distort the correlation but it still holds!

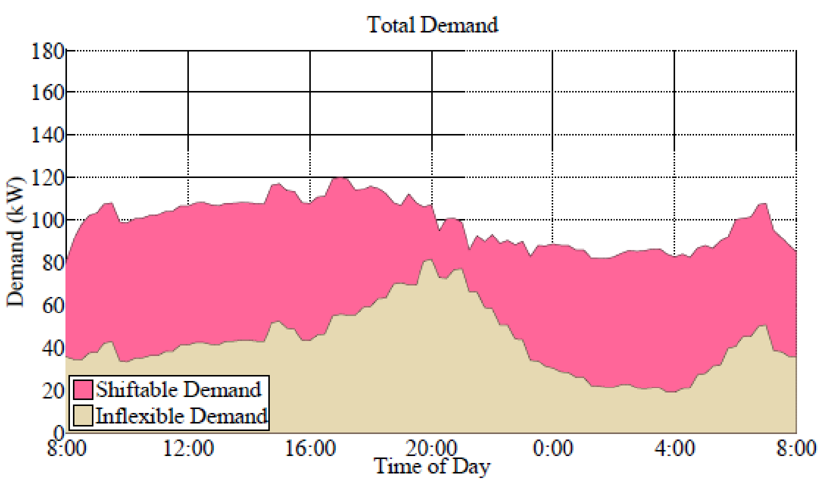
DM with Explicit Communication

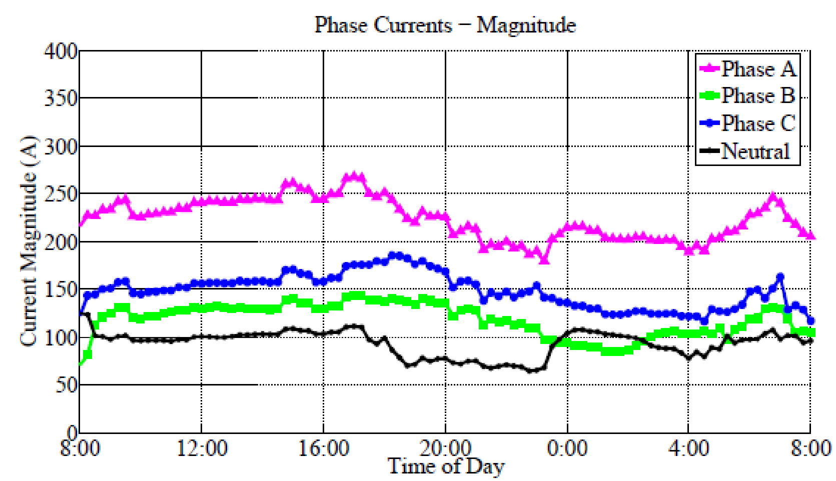


DM with explicit communication helps satisfying network constraints.

DM using Local Voltage Measurements

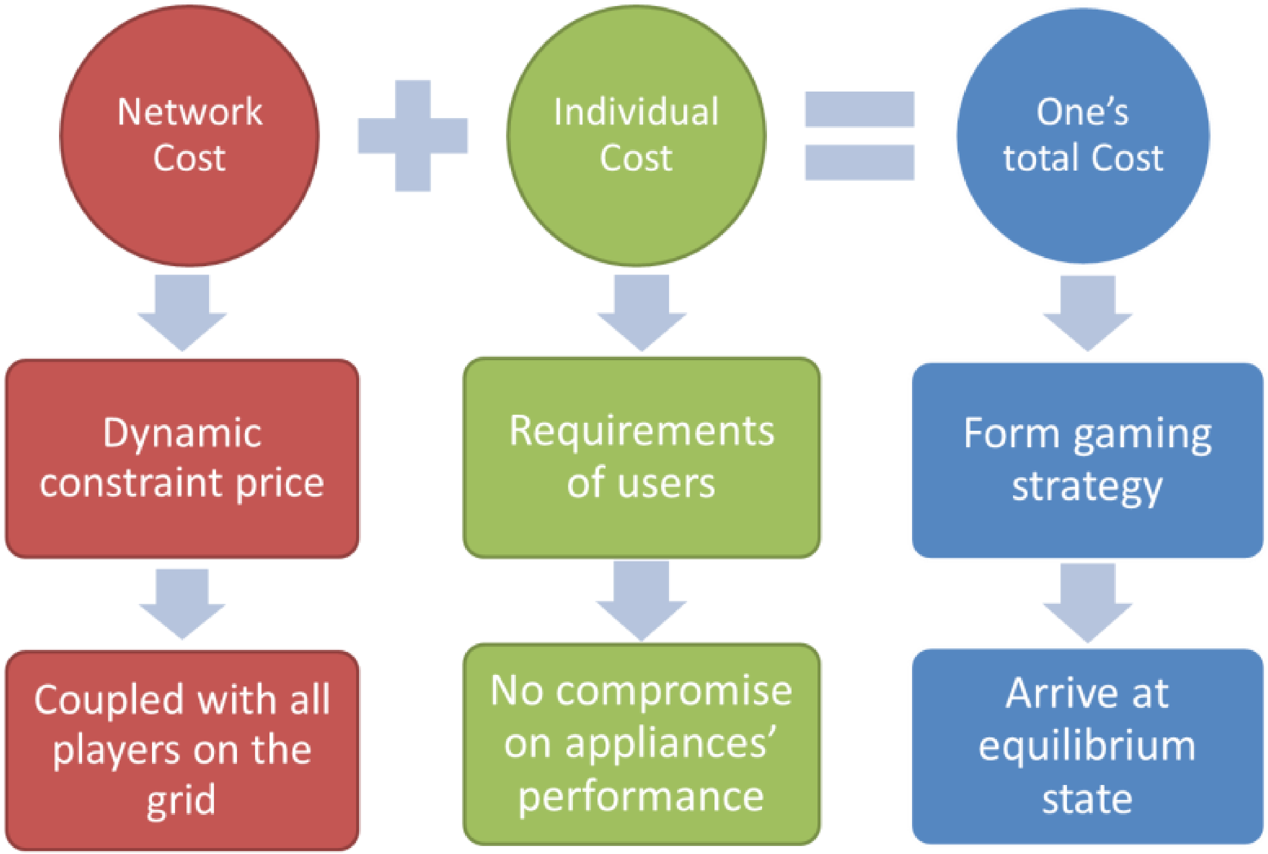






DM with implicit communication achieves the same result!

Game-Theoretic Approach

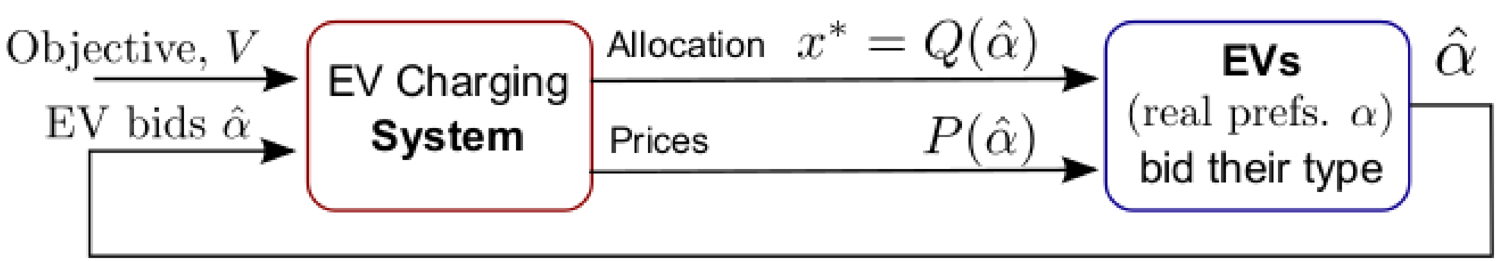


Mathematical model: individual users are modelled as players in a strategic game and are imposed prices reflecting network constraints.

EV Charging Mechanisms

Source: Tesla

- A Market Mechanism for Electric Vehicle Charging Under Network Constraints *(with J. DeHoog)*
- It allows vehicle owners to express individual preferences regarding their charging rates: those who want higher rates can charge early and faster but must pay a higher "price".
- The mechanism is shown to be efficient and strategy-proof, so users cannot gain an unfair advantage by misrepresenting their preferences.
- Real network models and real household and vehicle demand data are used to demonstrate the mechanism through simulations.



Conclusions and Ongoing work

Conclusions

- Game theory and distribution optimisation provide useful theoretical foundations for practically-relevant analysis of wholesale electricity markets and development of future demand management/response schemes.
- Analysis and models are verified as much as possible with real world data.

Ongoing work

- Analysis of the impact of microgrids and community energy on the distribution grid.
- Joint electrical and thermodynamic analysis of thermal inertia/storage and its impact on the grid.
- Stochastic modelling of intermittent generation and net demand using random variables and sequences to develop optimisation schemes beyond Monte Carlo simulations.

Thanks to all contributors

PhD students

- Mr. Amin Mazoumzadeh (current)
- Dr. Lu Xia (graduated)

Postdoctoral Researchers

- Dr. Ehsan Nekouei (now in Sweden)
- Dr. Julian De Hoog (IBM Research, AUS)

Colleagues

- Dr. Deb Chattopadhyay (World Bank, USA)
- Prof. Iven Mareels (UoM)
- and other collaborators over the years...

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Thank you!

Any questions?