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The Technological Feasibility and Economics of 100% Renewable Electricity for Australia

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(Based on research by Ben Elliston, Mark Diesendorf and Iain MacGill)

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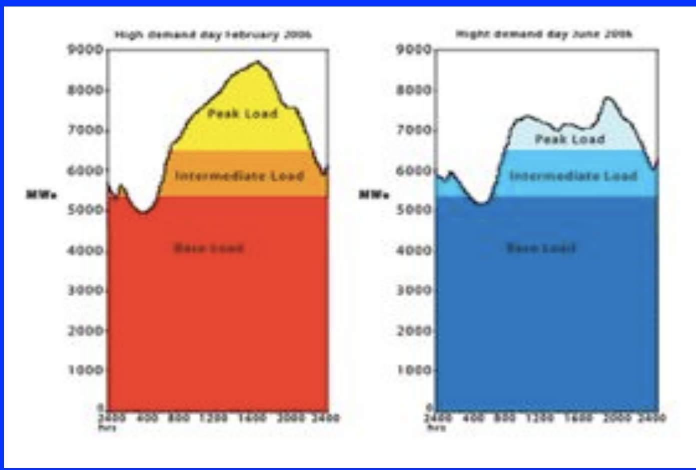
A Technical Challenge to Renewable Electricity Supply

- Some renewable energy sources are called 'intermittent' because they fluctuate, especially sunshine and wind
- These fluctuations are only partially predictable
- This 'intermittent' property is used as the basis of claims that 100% renewable energy is impossible
- Recent research from Europe, the USA and now Australia shows that this challenge can be solved, without major costs
- Part of the solution already exists in many electricity supply systems that track fluctuating demand without storing electricity

Typical Daily Demand Variation: Summer & Winter

Victoria, Australia



Conventional approach: Use base-load supply (coal, nuclear) to meet base-load demand. Claim that 100% RElec must await base-load renewable supply. 3

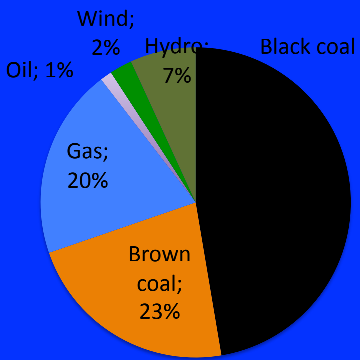
A Popular View of Australia

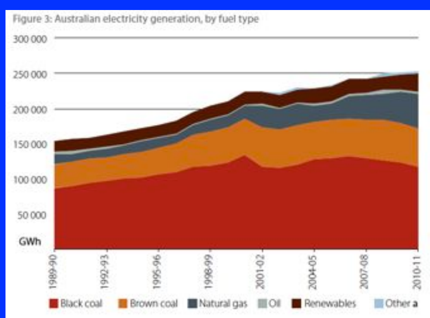
Plenty of sunshine (and skin cancer)

The Dark Side of Australia: Kingdom of Coal

- Biggest coal exporter in the world
- Until recently, 77% of Australia's electricity from burning coal
- Impacts from GHG emissions, air & water pollution, respiratory diseases, land degradation
- Pressure from vested interests => policies to cut emissions are seen as weak and tokenistic

Australian Electricity Generation by Fuel 2010-11 and Trend





In 2010-11, total generation 253 TWh; demand growth ceased in 2009-10; trend coal 70% ↓; gas 19% ↑; hydro 6.6%; wind 2.3% ↑; biomass 0.8%; solar 0.33% ↑; Source: BREE 2012

Concentrated Solar Thermal Electricity (CST)

- Low-cost thermal storage in molten salts or possibly concrete, graphite or ammonia
- Can generate overnight after a sunny day
- Needs direct sunlight
- Globally 1000 MW operating; 1000 MW under construction; 8000 MW advanced planning
- Mostly Spain, a few US states, MENA
- Trough systems are bankable
- Huge potential for Australia, s-w USA, n-w China, n-w India, MENA

354 MW trough system in California.

Gemasolar Power Tower with 15-Hour Storage in Molten Salt, Spain

- Higher temperature >500°C than troughs
- Hence more efficient
- Rated power 20 MW
- 15 hr thermal storage
- Capacity factor 63%
- Demonstration plant; not yet bankable

Simulations of 100% RElec in the NEM*

Stage 1: Technology and reliability

Researchers: Ben Elliston (PhD candidate), Mark Diesendorf & Iain MacGill

<u>Research question 1</u>:
Could the NEM have operated in 2010 using 100% renewable generation based on commercially available technologies?

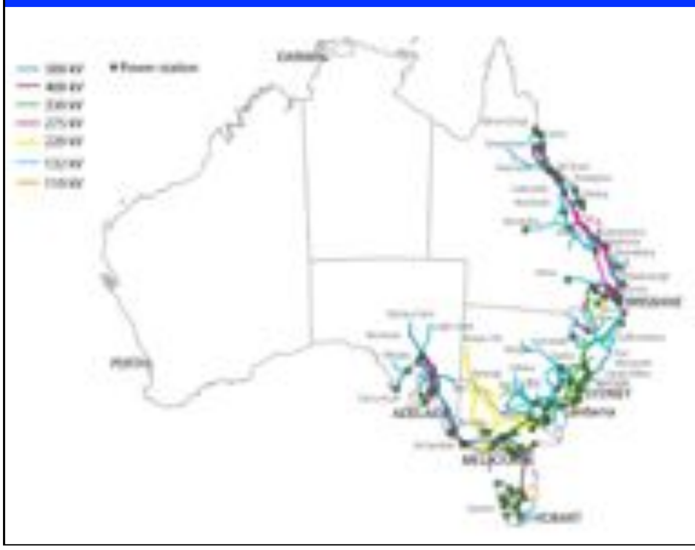
Method: Hourly computer simulation with real data on demand, wind & sunshine

*NEM = National Electricity Market

Simulation Model
Replaying a simplified version of reality

- Simulation computer program written by Ben Elliston in Python programming language. It has 3 components:
  - Framework supervising simulation; independent of the energy system
  - Integrated database of meteorology and electricity industry data
  - Library of simulated power generators
- 'Copper plate' assumption (initially)
  - Power can flow unconstrained from any generation site to any load site. Hence, demand across all NEM regions is aggregated, as is supply.
- Baseline renewable energy supply mix chosen by guided trial and error exploration

NEM Power Stations & Transmission Lines



- Long (5000 km), thin transmission system
- Weak links between states
- Best wind in southern region
- Best sun to west of transmission spines

Data Sources

Quantity	Source
Demand	AEMO: 30 min.data aggregated across NEM region and converted to hourly
Wind (existing wind farms in S-E)	AEMO: 5-min. data converted to hourly
Wind (hypothetical wind farms in N-E)	CSIRO: Air Pollution Model (TAPAM)
Solar	BoM: hourly satellite data for GHI & DNI
Other weather	BoM: temperature, humidity, etc.

Hourly wind, solar and other weather data inputted to NREL's System Advisor Model (SAM) to obtain CST and PV outputs in selected locations

Baseline Renewable Energy Generation Mix in Order of Dispatch

Technology	Installed capacity (GW)	% of annual energy demand (approx.)
Wind, capacity factor 30%	23.2	30
PV, flat-plate, rooftop, capacity factor 16%	14.6	10
CST with thermal storage, solar multiple 2.5, storage 15 hr, capacity factor ~60%	15.6	40
Pumped hydro (existing)	2.2	6
Hydro without pumped storage (existing)	4.9	
Gas turbines, biofuelled	24	14

Current installed capacity 45-50 GW

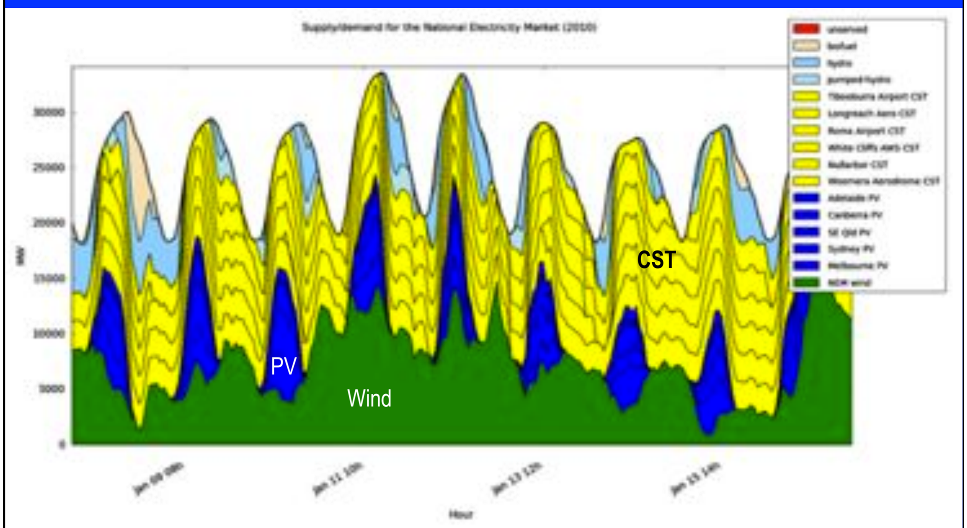
Baseline NEM Simulation of 2010 Demand

Summary of Results

Annual electrical energy demand (TWh)	204.4	NEM excludes Western Aust.
Spilled electricity (TWh)	10.2	
Spilled hours	1606	
Unserved energy (%)	0.002	equals NEM reliability standard
Unmet hours	6	All in winter
Electrical energy from gas turbines (TWh)	28	14% of demand (too large!)
Largest supply shortfall (GW)	1.33	4% of max. demand (too large!)
Maximum demand 2010 (GW)	33.6	

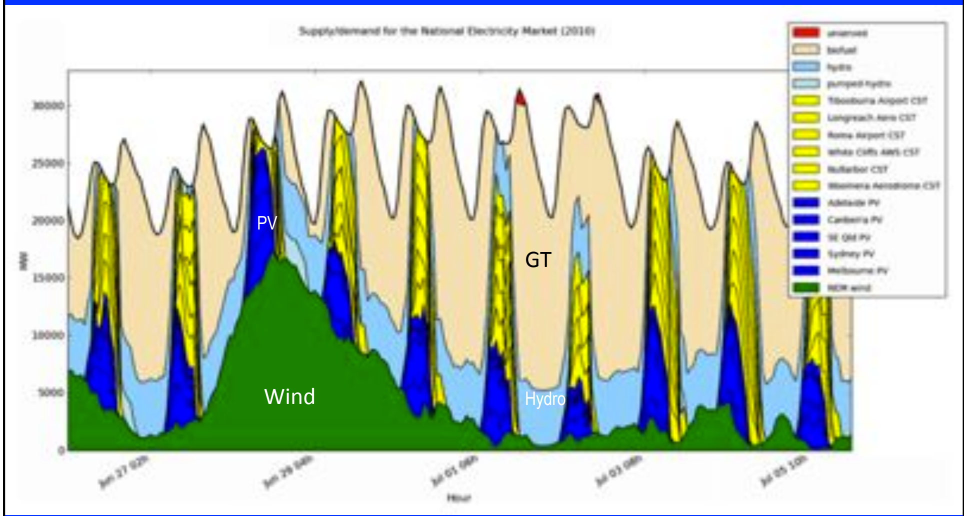
Each run through the 8760 hours of 2010 takes about 1 sec..

Supply and Demand for a Typical Week in Summer 2010 – Baseline Simulation



CST behaves like a fluctuating baseload power station in summer. Negligible GT energy used.

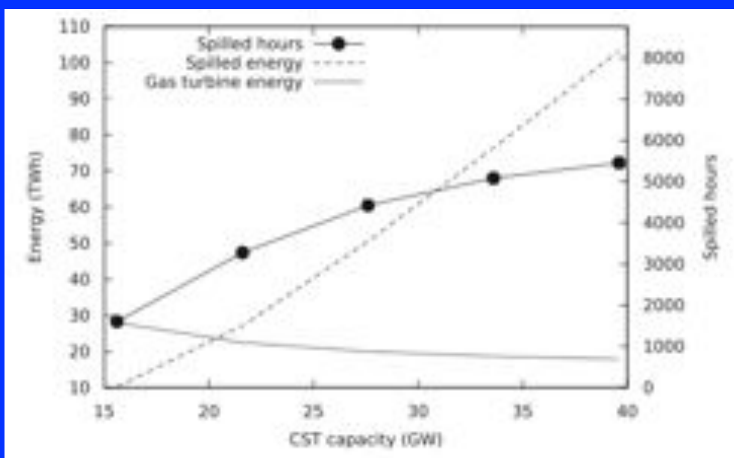
Supply and Demand for a Challenging Week in Winter 2010 – Baseline Simulation



CST does NOT behave like fluctuating baseload power station in winter. Much GT energy used.

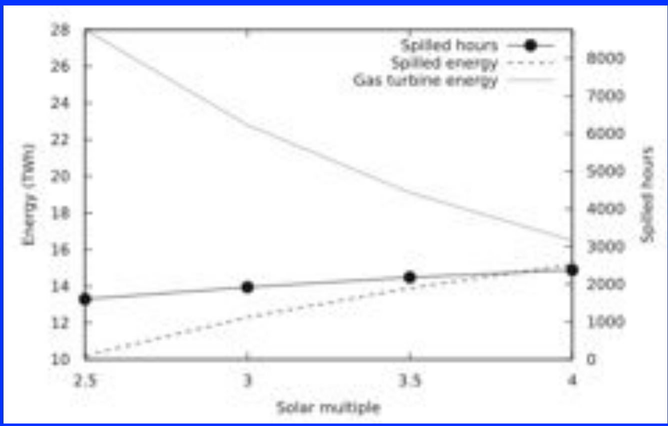
Effect of Increasing CST Capacity

with fixed solar multiple and hours of storage



Reduces gas turbine (GT) energy gradually and reduces unmet hours from 6 to 2.
But increases spilled hours & spilled energy and has high cost.

Effect of Increasing Solar Multiple of CST

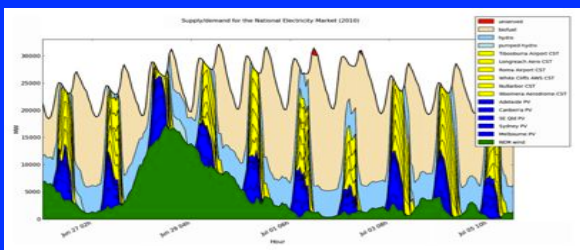


Reduces GT energy substantially – but at high cost.

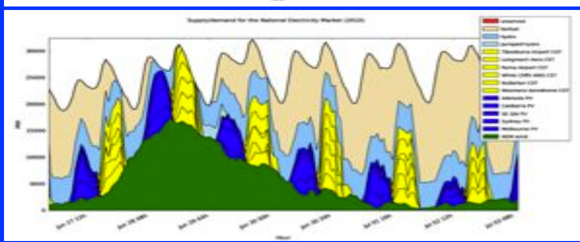
Effect of Time Delay in CST Winter Dispatch

More Solar Input goes into the Thermal Store

No time delay

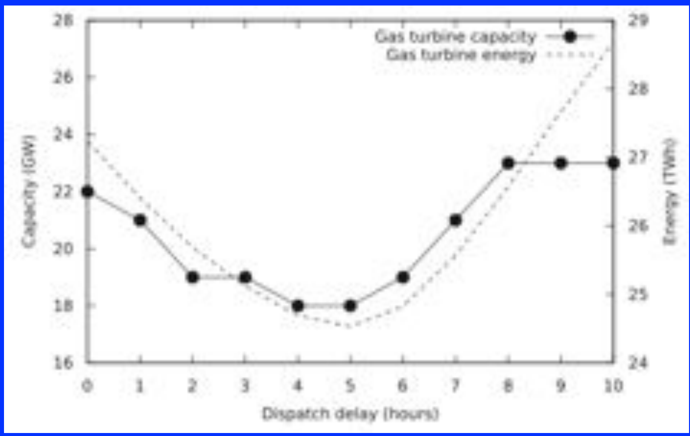


Time delay 7h reduces GT energy (and capacity)



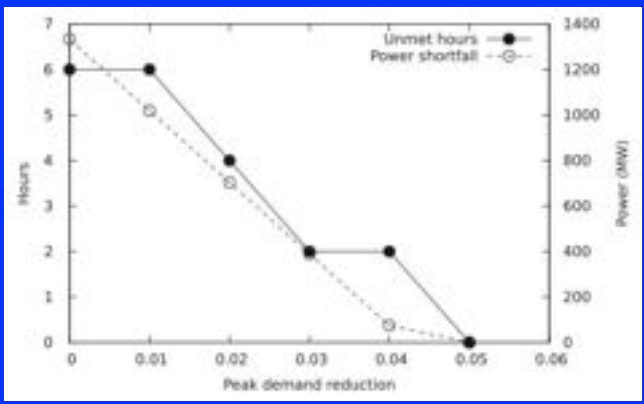
Effect of Time Delay in CST Winter Dispatch

More Solar Input goes into the Thermal Store



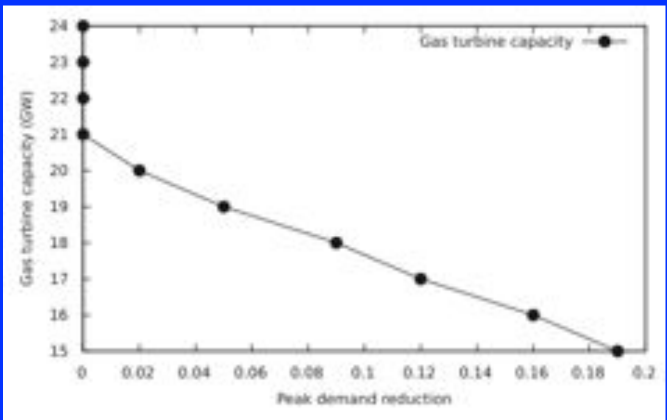
5-hr dispatch delay gives quite large reduction in GT energy use and capacity.

Reducing Demand Peaks increases Reliability



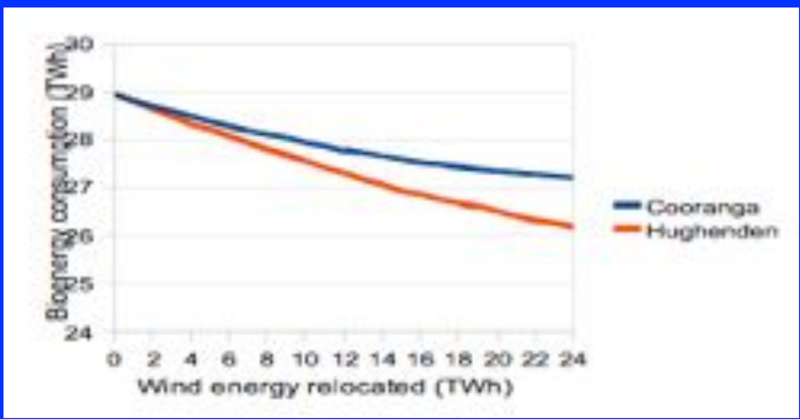
5% reduction in the 6 winter demand peaks, that produce unmet hours in baseline simulation, eliminates all unmet hours and unmet power. GT capacity is fixed.

Reducing Demand Peaks Reduces Required GT Capacity when Reliability is Fixed



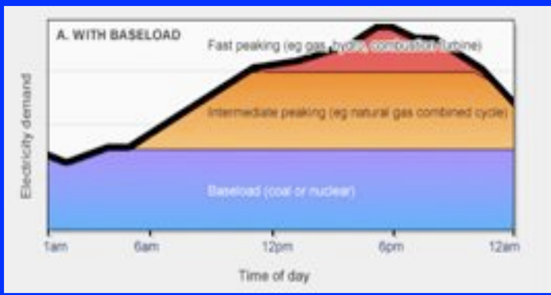
By reducing GT generating capacity from 21 GW to 15 GW, the NEM reliability standard can be met if demand during the unmet hours is reduced by 19%. GT energy shrinks by 4%.

Effect of Greater Wind Diversity on Bioenergy Generation in Gas Turbines

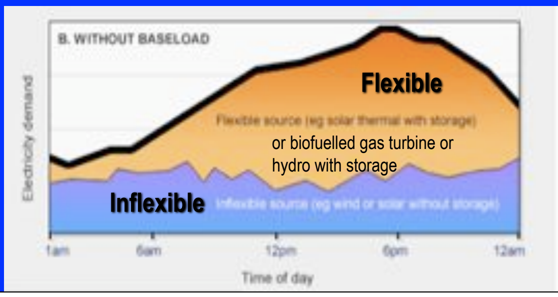


Cooranga & Hughenden are possible sites in Queensland (north-eastern Australia), far from the existing wind farms in south-eastern Australia.

Meeting Demand without Baseload Stations



Old concept: With baseload power stations



New concept: No baseload power stations

Meeting Demand without Baseload Stations

- RElec supplied by mix of inflexible plants (eg, wind and PV without storage) and flexible plants (eg, CST with thermal storage, hydro with storage, biofuelled gas turbines)
- Flexible plants (together with improved weather forecasting) handle the fluctuations in power output from inflexible plants
- Demand management in a 'smart grid' can also play an important, low-cost role.
- The key parameter is reliability of the whole supply-demand system, not reliability of individual technologies

Stage 2 Simulations: Economics

- Optimise economics while varying renewable generation mix and their locations in regions (states)
- Calculate overall annual cost of meeting hourly 2010 demand, including annualised capital costs and operation & maintenance costs
- Remove 'copperplate' assumption, treating each State separately together with hypothetical unconstrained principal transmission links
- Use a real-valued genetic algorithm to search for lowest annualised cost generation mix that meets reliability standards and other constraints
- Constraints:
  - Reliability standard
  - Hydro limited because of fluctuations in annual rainfall
  - Limited bioenergy generation in GTs

Genetic Algorithm

- A search technique that emulate evolutionary process of breeding & natural selection to find 'fittest' individual according to specified constraints.
- Used Python toolkit called Pyevolve. Programmer supplies only a suitable genetic representation for each 'individual' (set of generators) and an evaluation function to score the 'fitness' of each individual.
- Evaluation function gives projected annualised cost of meeting 2010 demand in 2030 in 2012 AUD billions.
- Many simulations are run as the parameter space is explored. Parameter space comprises variable mix of RE generators and their locations.
- GA searches for individual with *lowest* fitness score (annualised capital + operating cost).

Initial Comparison Scenario

- Replace existing fossil fuelled power stations with most efficient commercially available fossil power stations
- Calculate annualised capital + operating cost to meet 2010 demand
- Assume carbon pricing would not alter generator dispatch
- Note: GHG emissions fall 19% compared with present generator mix (many ageing coal-fired power stations)

Projected 2030 Costs of Electricity Generation

Initial comparison between new 100% renewable scenario and new 'efficient' fossil scenario

Technology	Efficiency (GJ/MWh)	Capital cost ($/kW)	Fixed O&M ($/kW/yr)	Var. O&M ($/MWh)
Supercritical black coal	8.57	2947–3128	59	8
Supercritical brown coal	10.59	3768	71	9
Combined cycle GT	6.92	1015–1221	12	5
Open cycle GT (gas)	11.61	694–809	5	12
Open cycle GT (biofuel)	11.61	694–809	5	92
On-shore wind		1701–1917	40	14
CST		5622–6973	65	23
PV		1482–1871	25	0

Source: Australian Energy Technology Assessment (2012) with CST costs adjusted to 15h storage and solar multiple 2.0
Note: Costs in 2012 AUD

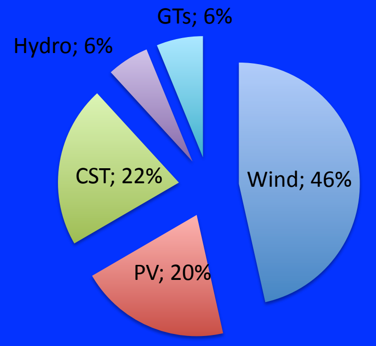
Sensitivity Analysis

Variable	Low value	High value
RE technology cost	Low	High
Discount rate	5%	10%
Additional transmission spines	No	Yes: SA-Qld and SA-NSW

Preliminary Results (under review by a journal)

Generation Mix by Energy for the 'Fittest' Individuals

Low Cost RElec Scenario; 5% Discount Rate; No extra transmission

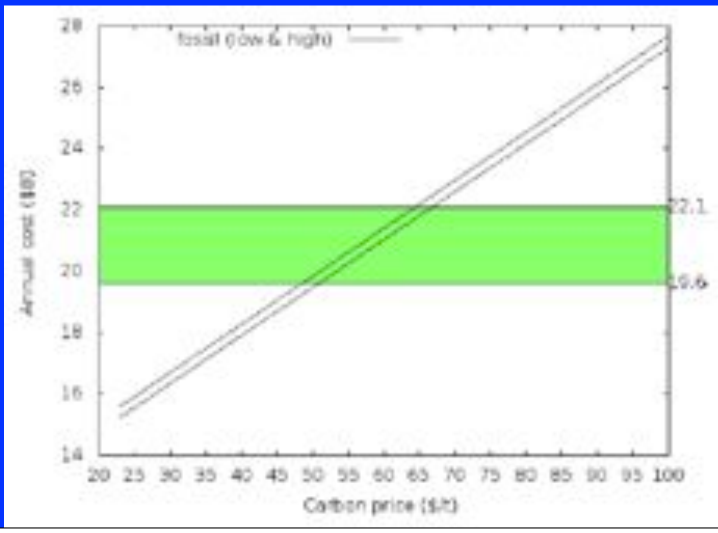


High cost scenario has higher % energy from wind and less solar.
High discount rate has little effect on generation mix.

Preliminary Results

Annual Costs: 5% Discount Rate

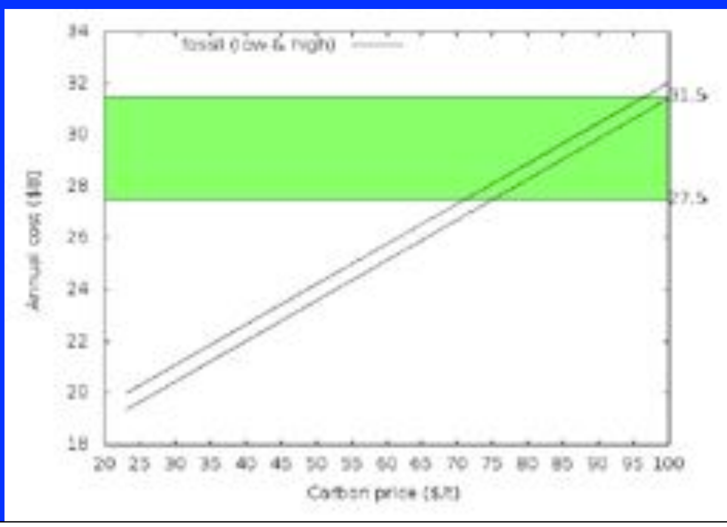
Bands show uncertainty ranges in costs. Green band is RElec.



Preliminary Results

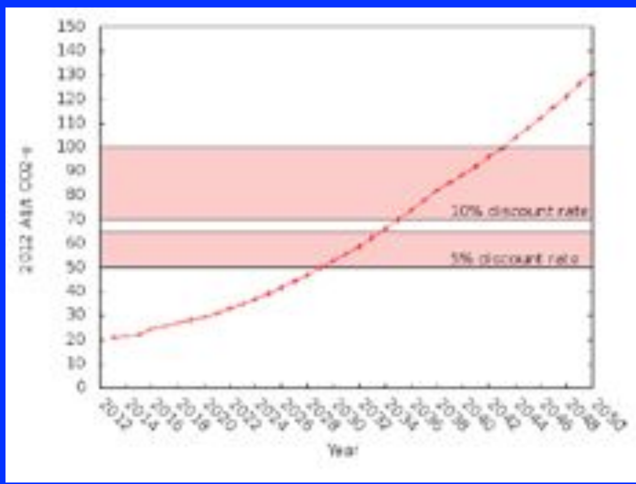
Annual Costs: 10% Discount Rate

Bands show uncertainty ranges in costs. Green band is RElec.



Preliminary Results

Breakeven Carbon Prices



Red line is Australian Treasury (2011) modelling of carbon price in 2012 A$/t CO2e – outdated?

Context of Breakeven Carbon Price

- Direct economic subsidies to fossil fuels > A$10 billion/yr in Australia
- Indirect subsidies = externalities of fossil fuel use
  - Climate change
  - Air pollution
  - Health impacts, especially respiratory diseases
  - Water pollution
  - Land degradation
- Subsidies to renewable energy in Australia are very small, mostly the certificate scheme associated with 2020 renewable electricity target of 41 TWh/yr

Effect of Adding Transmission 'Spines'
on Annualised Costs (2012 billion AUD)

Discount rate	Low cost ($B)	High cost ($B)	Low cost ($B)	High cost ($B)
	Without transmission costs		With transmission costs	
5%	19.6	22.1	21.2	24.4
10%	27.5	31.5	31.2	35.4

Conclusion re Simulations
Within the assumptions of the model…

- The Australian NEM could be run on 100% renewable electricity, based on commercially available technologies, while maintaining generation reliability
- Principal challenge is meeting peaks in demand on winter evenings following calm overcast days: handled best with GTs and/or demand management and/or smart operations of CST with storage
- Using projected 2030 prices of technologies and comparing with a highly efficient fossil fuel mix, the breakeven carbon prices are AUD 50-65/t CO_2e for 5% discount rate and 70-100/t CO_2e for 10% **(preliminary results)**
- These must be weighed against the costs of business-as-usual (both indirect and direct) and alternative low-carbon scenarios
- The principal barriers to 100% RElec in Australia are neither technological nor economic

Further Simulation Research Needed

- Compare with other non-renewable scenarios: eg, gas, nuclear (in progress)
- Extend database of demand, sunshine and wind to additional years to 2010 or run Monte Carlo simulations
- Improve spatial resolution of data, eg, geographic dispersion of RElec generators
- Do transmission in more detail

Another Project: Non-Technical Strategies for Rapid Climate Mitigation

- PhD research in progress by Laurence L. Delina
- What if a climate disaster drives the nations to undertake urgent, rapid and effective climate mitigation?
- Developing contingency plans for Australian governments, business and NGOs
- Focusing on government institutions, governance processes, culture, motivation, communication and finance
- Exploring what we can learn from rapid socio-economic restructurings in World War 2 and other events

Danke!

Questions and comments welcome

Further Reading

Elliston, Diesendorf & MacGill (2012) 'Simulations with scenarios with 100% renewable electricity in the Australian National Electricity Market. *Energy Policy* 45:606-613;

Elliston, MacGill & Diesendorf (2012, submitted) 'Least cost 100% renewable electricity in the Australian National Electricity Market'.