Transition to 100% Renewable Electricity on the SWIS – can it be done and at what cost?

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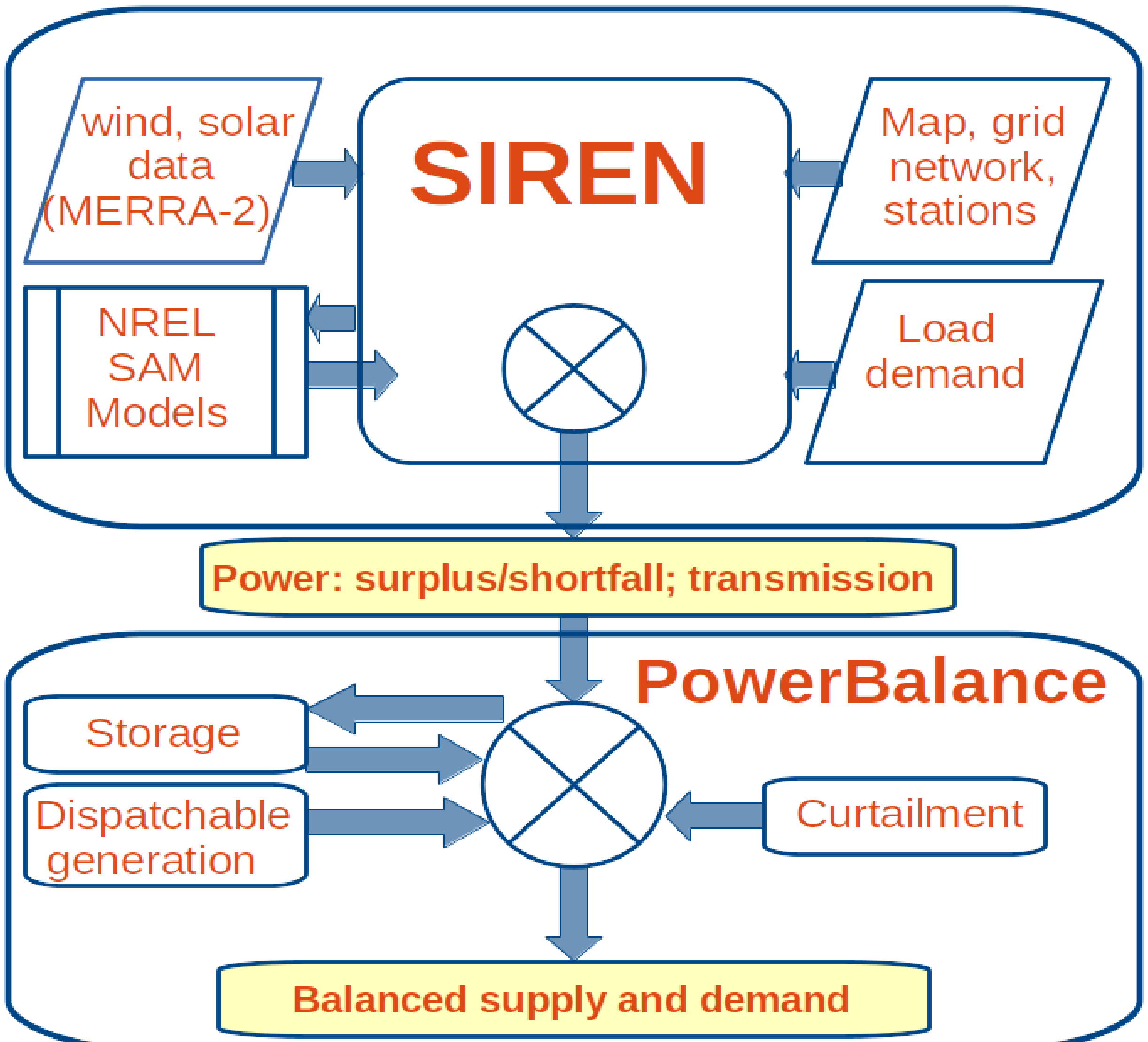
"We are looking at how to manage the system to be more resilient as well as … cost effective and carbon neutral, or zero carbon … (they) are not necessarily antithetical," ……..Nor is having renewable resources and having a reliable and secure system antithetical. In fact, you can have it all"

Australian Energy Market Operator CEO Audrey Zibelman

10 questions about renewable electricity (RE)

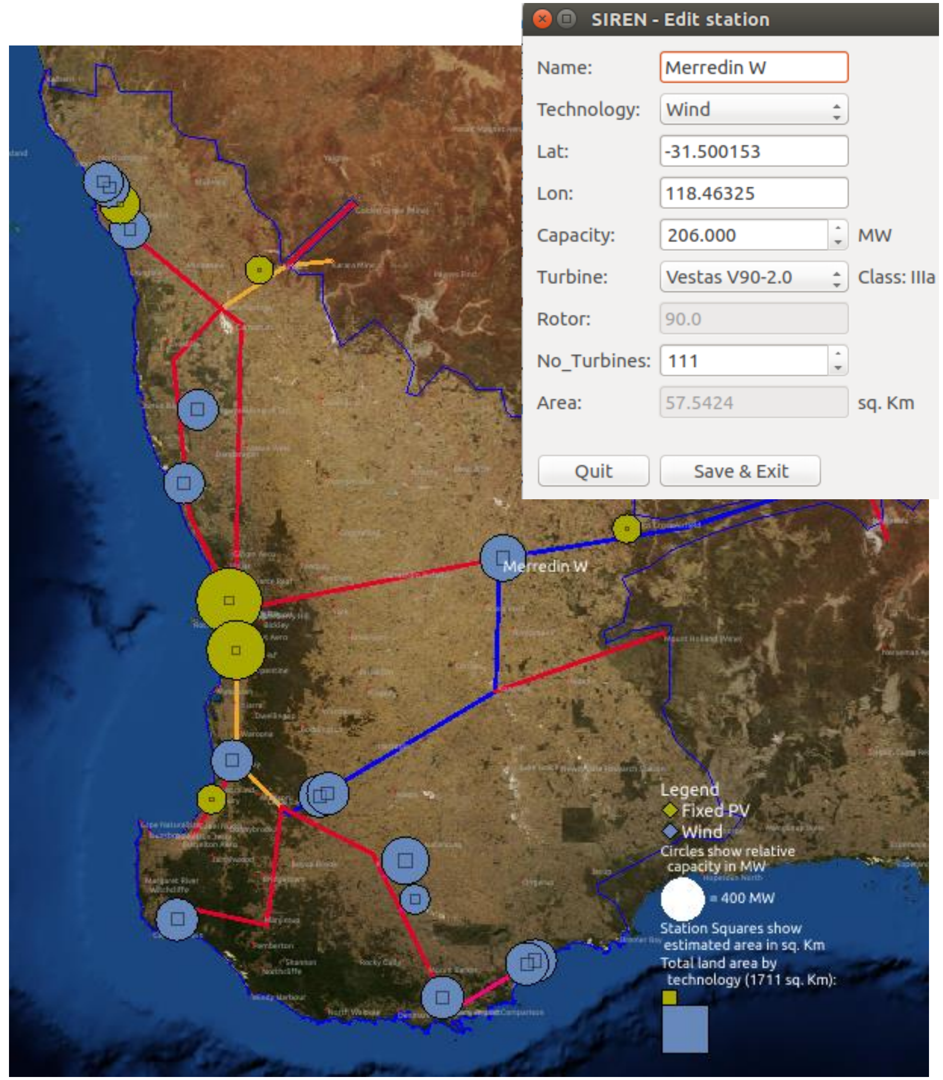
1. How are RE grids modelled using SIREN - Powerbalance?
2. Is 100% RE achievable and if so how?
3. How much RE - wind, solar and storage capacity - is needed to replace coal and gas steam thermal and what is the optimal target for RE?
4. What will renewable electricity cost?
5. Does coal or gas steam thermal have a future with RE?
6. But isn't RE mainly about reducing carbon emissions?
7. How variable is renewable energy?
8. How and where can wind be most effective?
9. What type of solar to use?
10. What about the cost of new transmission lines?

SIREN Toolkit Process Flow



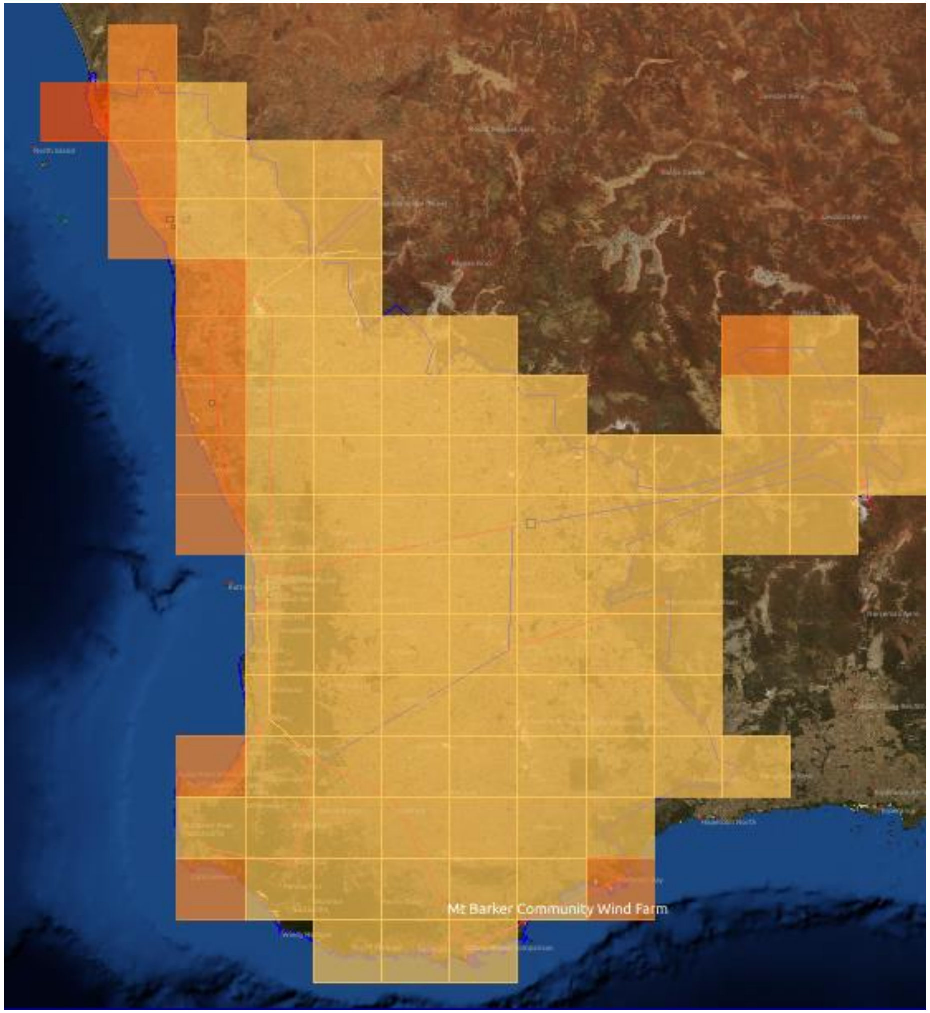
The SIREN Model

- Sophisticated computer model with simple user interface
- Users explore potential location and scale of renewable energy sources (stations, storage, transmission) to meet electricity demand
- Can be based upon existing network
- Enables rapid development of renewable energy scenarios using robust models



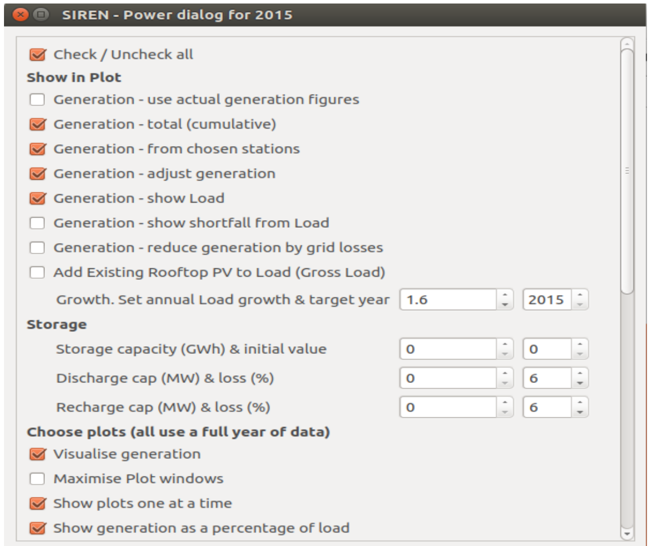
Weather affects generation

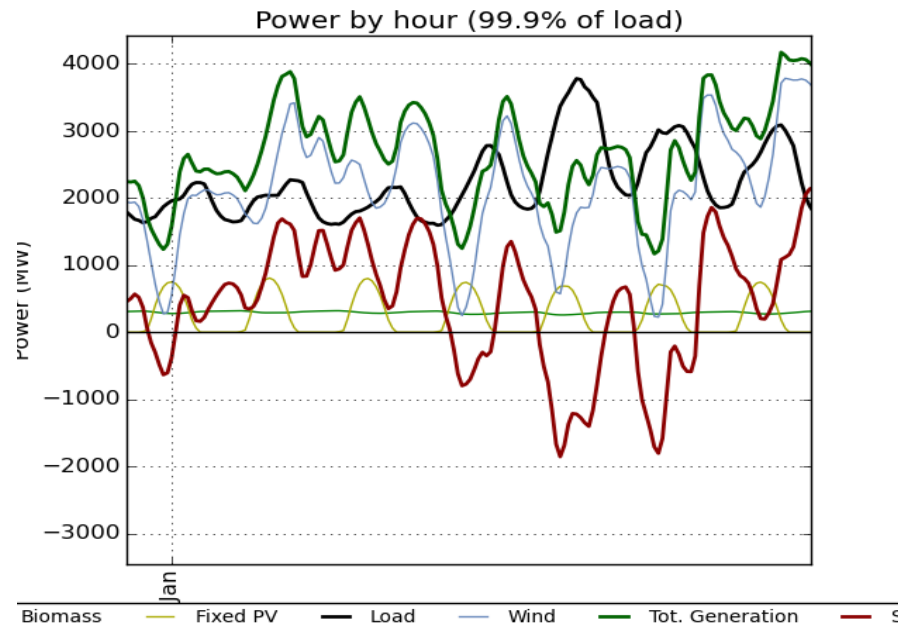
- Weather data that reflects actual weather conditions of the past enables any model to better map actual load demand with “supply”
  - For example, hot weather increases air conditioning load
- NASA MERRA-2* data
  - NASA re-analysed satellite data
    0.5º lat x 0.625º lon
    (~ 55km x 0-69 km)
  - A source for worldwide solar and wind data

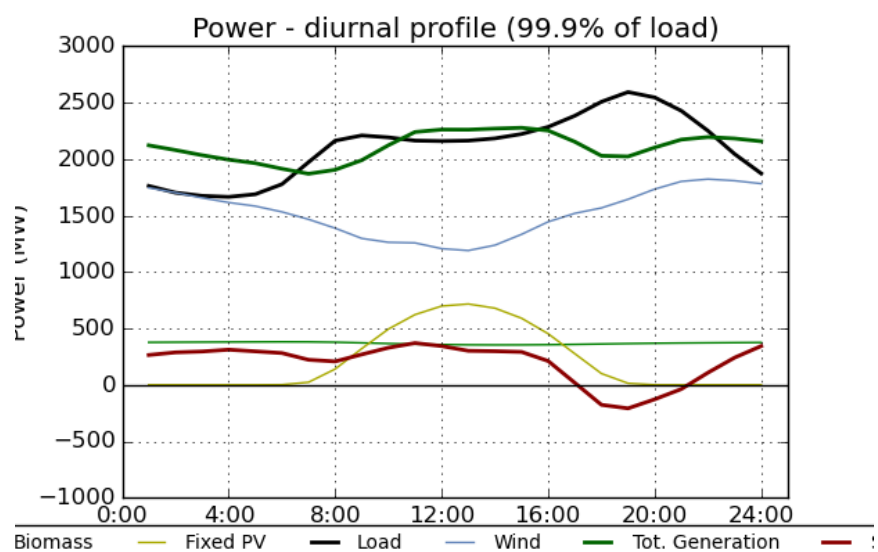


* Modern-Era Retrospective analysis for Research and Applications, Version 2-

Model Power generation





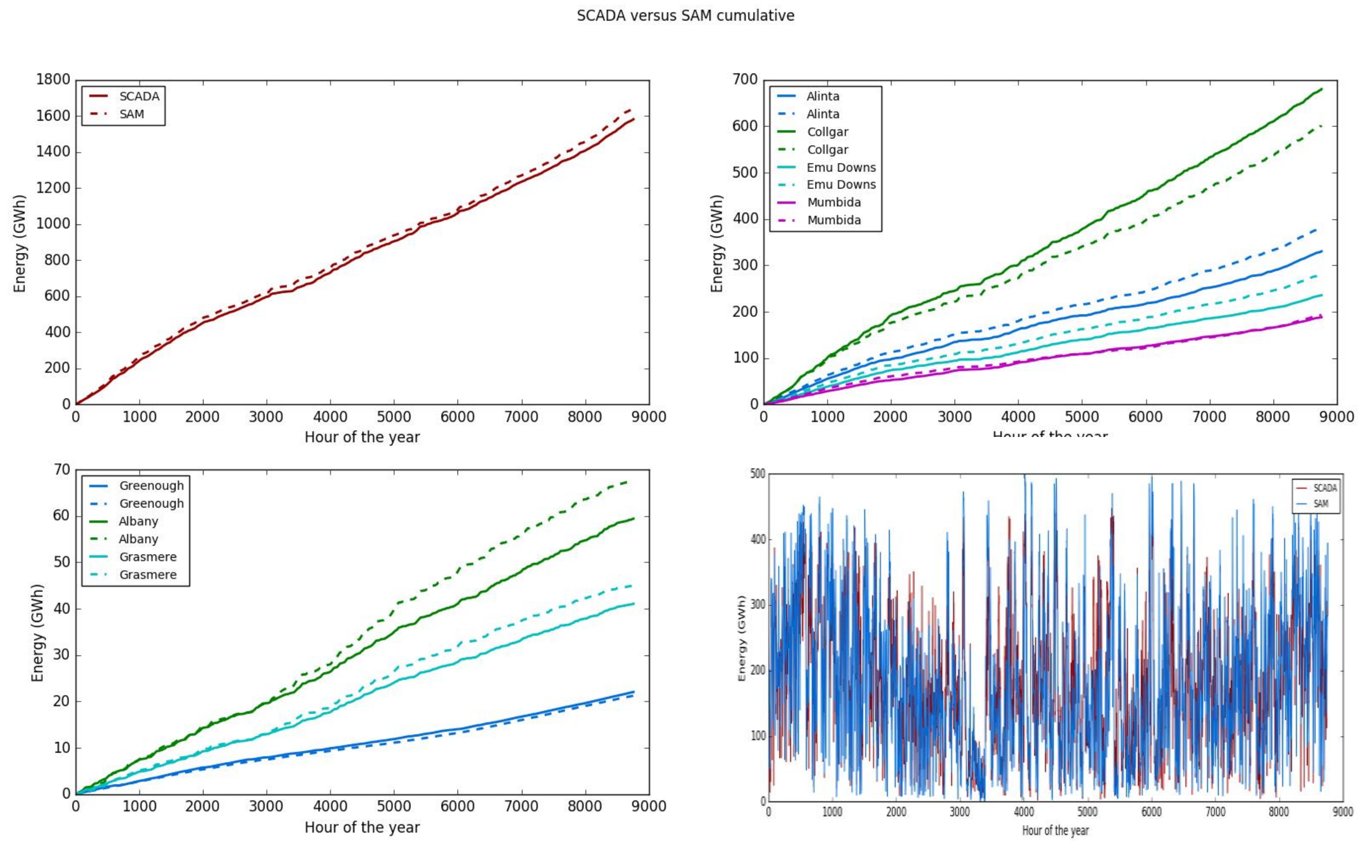


- System Advisor Model (SAM) models from US DoE National Renewable Energy Laboratory (NREL)
- Run SAM model for each station and produce combined result
- Match generation to Load

How does it compare?

Validated SAM calculated generations with actual generation (2014)

- Average correlation is 0.77 (0.70-0.83 for wind, 0.95 for the one utility scale PV farm)
- Validates usage of NREL SAM models and NASA MERRA-2 data
- Correlation of actual generation with calculated gives confidence to use this approach



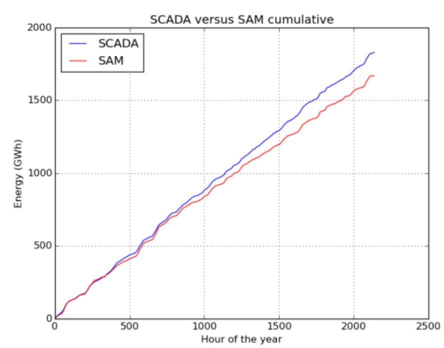
Robust models - Predicability

SWIS Correlation SAM to SCADA

Year	Corr.
2007 (3)	0.76
2008 (3)	0.72
2009 (3)	0.74
2010 (3)	0.74
2011 (3)	0.74
2012 (6)	0.70
2013 (8)	0.73
2014 (9)	0.77
2015 (9)	0.73
2016 (9)	0.78
2017 (9)	0.78
2018 (9)	0.79

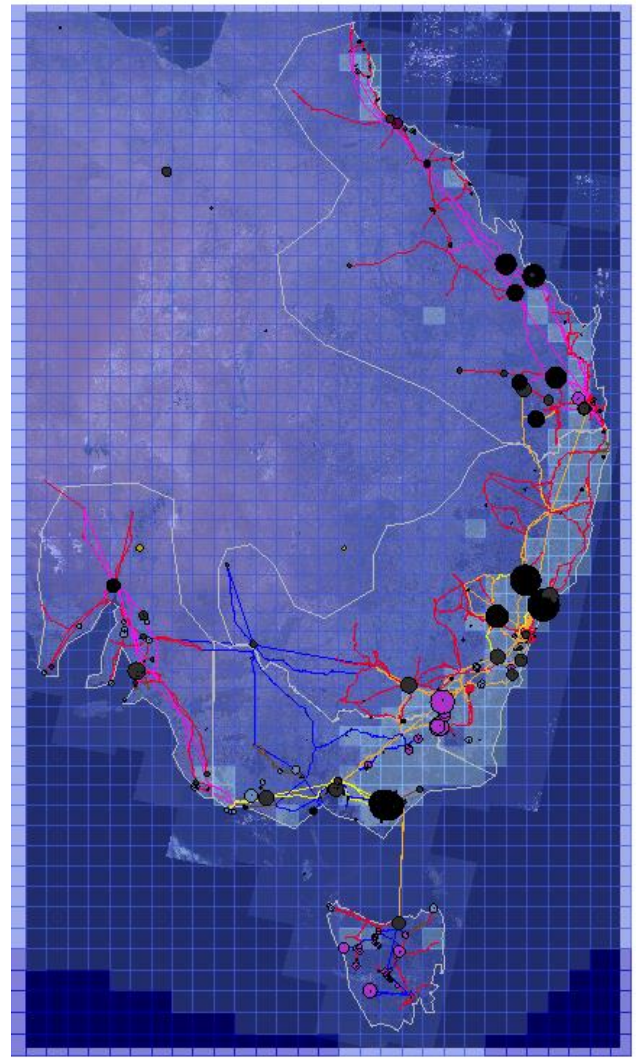
NEM Correlation

Year	Corr.
2015 (27)	0.70



Future Forecasting (AEMO)

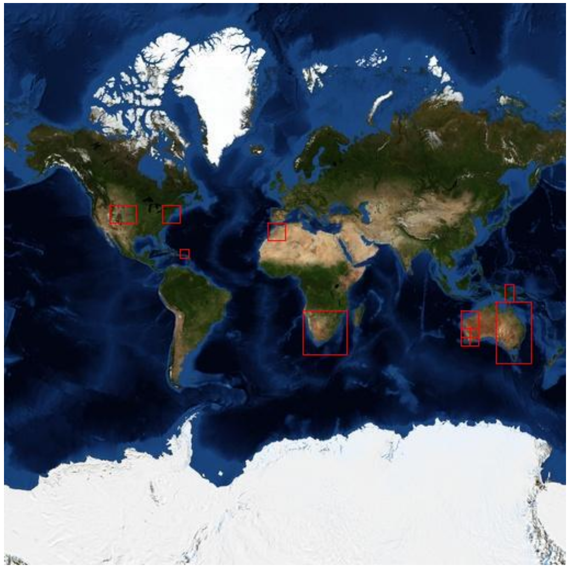
- ASEFS
- AWEFS



Scale to Requirements

Wide & Open Application

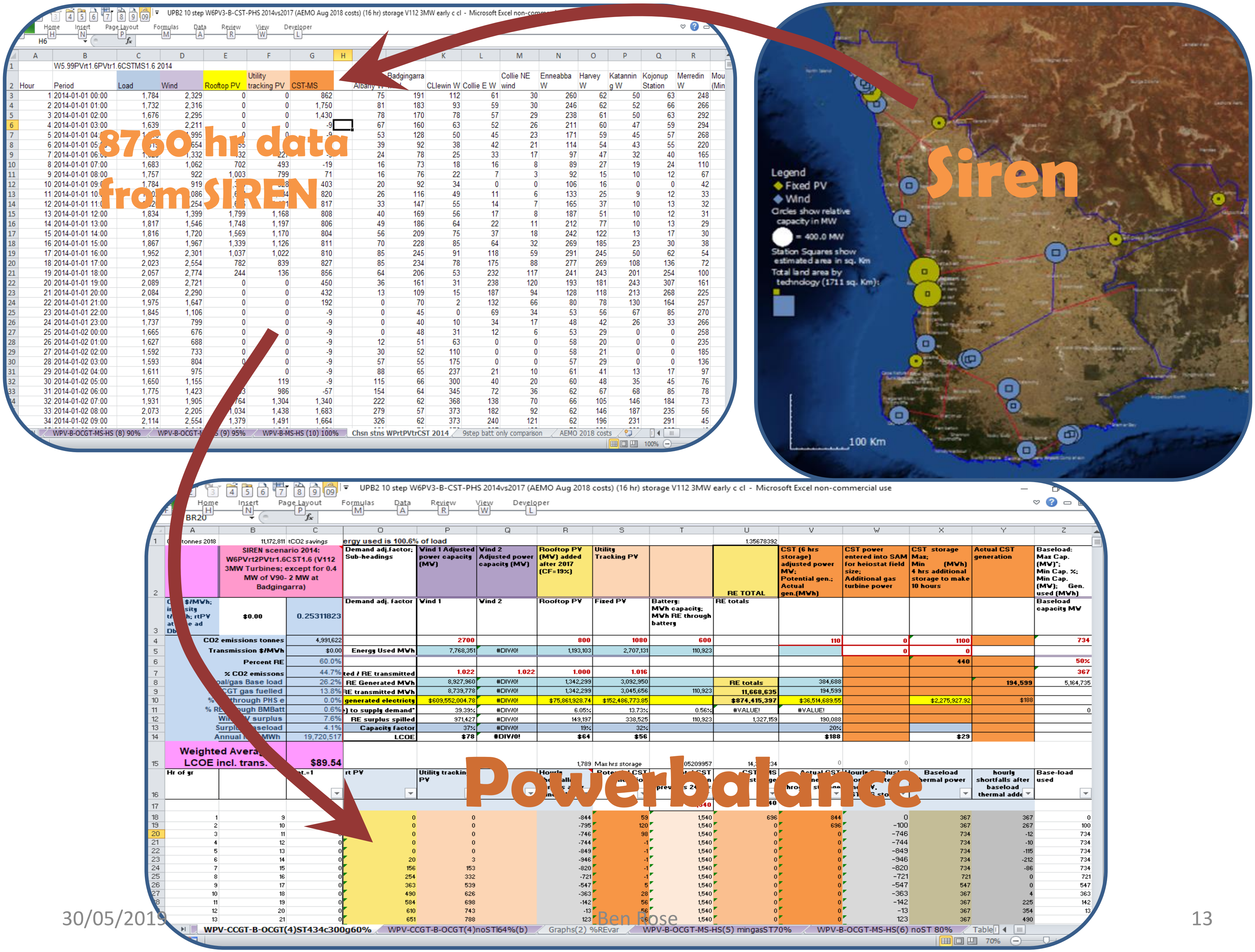
- Data sources are publicly available
  - Models – NREL SAM
  - Maps – OpenStreet Map (MapQuest)
  - Weather – NASA MERRA-2
  - Network – Location/area dependent
- Developed to support any geographic area
- Developed with open source products
  - Python with it's extensive range of libraries
  - Packaged binaries sourceforge.net/projects/sensiren/
  - (Includes package to create SAM weather files from MERRA-2)
- Licensed under the GNU
  - GNU Affero General Public License



SIREN - Powerbalance Toolbox was used to model and cost these scenarios for transition to Renewable Electricity

- **Powerbalance** is a set of programmed Excel spreadsheet templates for scenario types.
- A tool to quantify and cost dispatchable energy generation, storage and CO2 emissions.
- Balances power with load for 8760 hours of a year.
- Produces costed RE scenarios.
- Tool to develop whole of system plans for electricity grids

**Invented by Ben Rose and Len Bunn*


8760 hr data
from SIREN
Siren
Powerbalance

Technical / economic transition plans for renewable electricity

NEM :

- Bin Lu, Blakers, Bin Lu et al, ANU, 2017 (using 'NEMO')
- Elliston et al, 2016, UNSW, ('NEMO')

WA:

- SWIS - This plan and variants (SIREN-Powerbalance)
- Kimberley – TWS RE roadmap (SIREN-Powerbalance)

Synergy is using Plexos for modelling

SA modelling by Danny Price

WA State Government does not yet have such a plan but have started – Whole of System Plan, Distributed Energy Roadmap.

Modelled costs for 2021-22: Gas $7/MJ; Coal $3.00 /MJ

New RE and storage CAPEX, see below; WACC 6%

Build cost ($/kW) real 2017 dollars

Cost to construct new generation, not including connection costs. Battery installations assume energy storage of 2kWh/kW. Pumped hydro installations assume energy storage of 6kWh/kW

Slow and rapid scenarios use the Neutral cost trajectories, except for technologies specified

Neutral

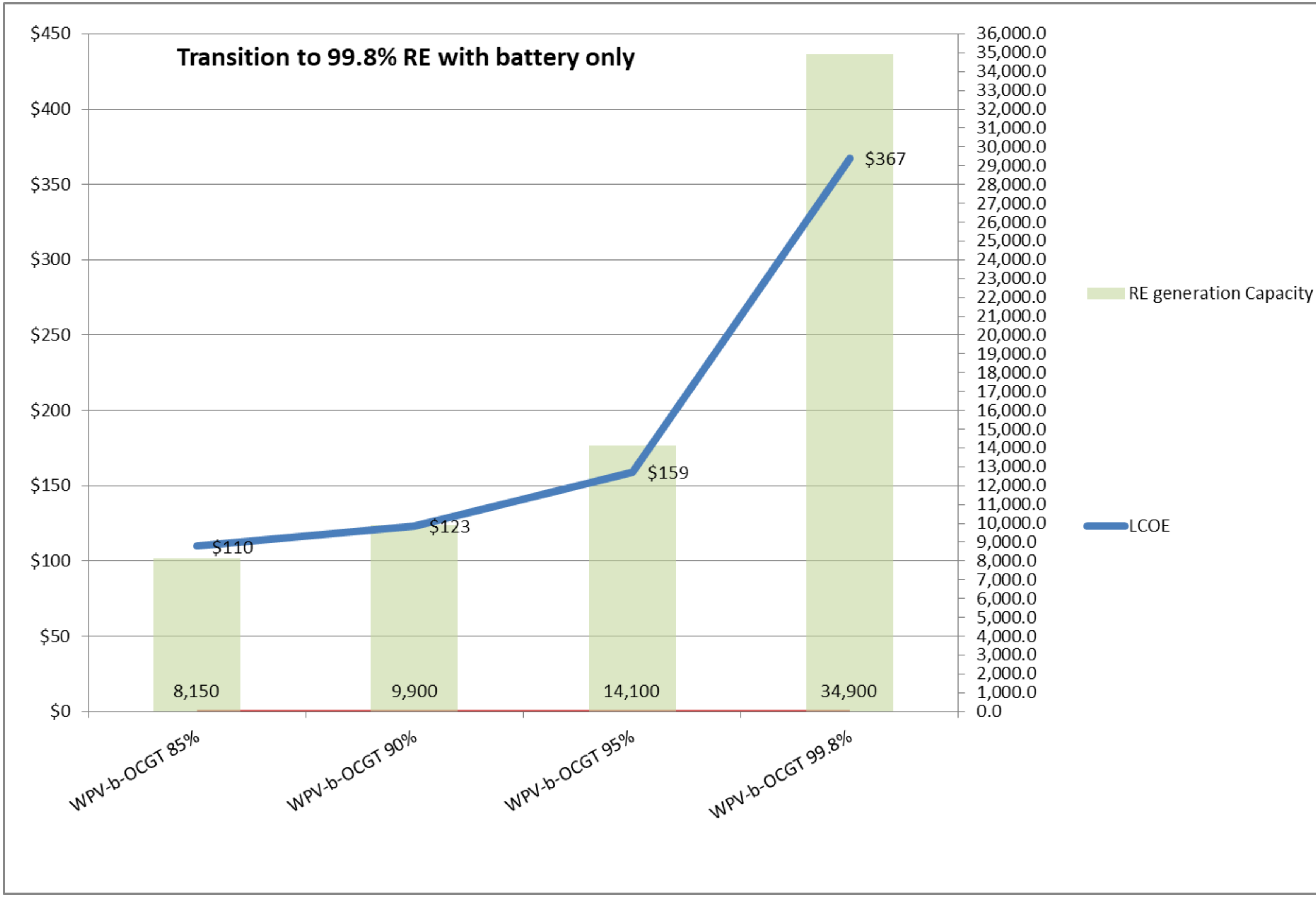
	2017-18	2018-19	2019-20	2020-21	2021-22
CCGT	$ 1,500.68	$ 1,500.66	$ 1,500.66	$ 1,500.41	$ 1,500.30
OCGT	$ 1,019.61	$ 1,014.51	$ 1,009.44	$ 1,004.39	**$ 999.37**
Single-axis Tracking Solar PV2	$ 1,952.05	$ 1,733.25	$ 1,634.67	$ 1,492.50	**$ 1,421.39**
Solar Thermal Central Receiver (6 hrs storage)	$ 4,434.41	$ 3,677.62	$ 3,299.20	$ 3,299.20	**$ 3,299.20**
Wind	$ 1,945.06	$ 1,940.42	$ 1,933.93	$ 1,924.78	**$ 1,921.10**
Pumped Hydro (6hrs storage)	$ 1,386.11	$ 1,379.18	$ 1,372.29	$ 1,365.42	**$ 1,358.60**
Large Scale Battery Storage (2hrs storage)	$ 1,480.18	$ 1,313.14	$ 1,208.39	$ 1,166.77	**$ 1,143.42**

AEMO, Aug 2018. Integrated System Plan Modelling Assumptions

Existing fossil plant WACC 8%. CAPEX: Collie, Blue Waters as published, Muja 0 (paid off); CCGT $1187/kW; DSM $300/MWh

Is 100% renewable energy achievable on the SWIS and if so how?

To achieve 100% RE without storage would be prohibitively expensive



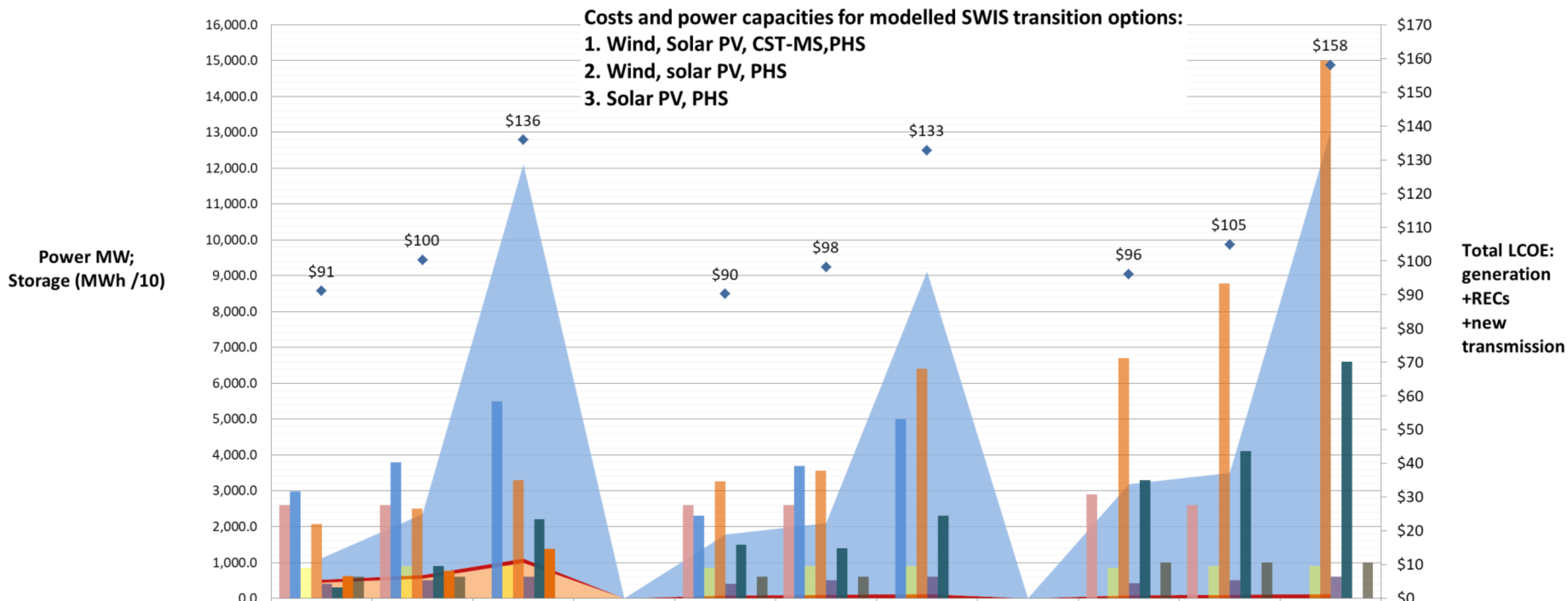
Modelling indicates there are options with storage that can achieve 100% RE at a reasonable cost. However the large pumped hydro storages required for 100% RE may not be physically practical.

Three modelled scenarios for 80%, 90% and 100% RE are shown in the next graph:

1. Wind, Solar PV, solar concentrating thermal (CST) with molten salt storage (MS), pumped hydro storage (PHS), battery storage (Batt) and fast ramping gas turbines (OCGT)
2. Wind, Solar PV with PHS, Batt, OCGT
3. Utility scale tracking solar PV only with PHS, Batt, OCGT

A transition to 100% RE using Option 1 is explained in further detail in this presentation.

Costs and power capacities for modelled SWIS transition options



	Wind - PV - Batt-OCGT-MS-PHS; 80%RE	Wind - PV - Batt-OCGT-MS-PHS; 90%RE	Wind - PV - Batt-OCGT-MS-PHS; 100%RE	Wind - PV - Batt-OCGT-PHS; 80% RE	Wind - PV - Batt-OCGT-PHS; 90% RE	Wind - PV - Batt-OCGT-PHS; 100% RE	PVtr only - Batt - PHS - OCGT; 80% RE	PVtr only - Batt - PHS - OCGT; 90% RE	PVtr only - Batt - PHS - OCGT; 100% RE
Hydro storage (MWh*10)	600	1,700	11,000	1,700	2,000	9,000	3,100	3,400	12,900
Batt storage (MWh*10)	80	100	120	80	100	120	85	100	120
Conc. Solar Thermal (MW)	440	550	990	0	0	0	0	0	0
Gas OCGT fast ramping (MW)	2,600	2,600	0	2,600	2,600	0	2,900	2,600	0
Wind (MW)	2,980	3,800	5,500	2,300	3,700	5,000	0	0	0
PV rooftop (additional to 400 MW in 2014)	850	900	900	850	900	900	850	900	900
PV tracking (MW)	2,080	2,510	3,300	3,260	3,560	6,400	6,700	8,780	15,000
Battery (MW)	400	500	600	400	500	600	425	500	600
Pumped Hydro (MW)	300	900	2,200	1,500	1,400	2,300	3,300	4,100	6,600
Molten Salt storage (MWh*10)	616	770	1,386	0	0	0	0	0	0
Demand side management (DSM)	600	600	0	600	600	0	1,000	1,000	1,000
LCOE of generation (2014)	91	100	136	90	98	133	96	105	158
TOTAL RE CAPACITY MW	7,050	9,160	13,490	8,310	10,060	15,200	11,275	14,280	23,100

Standby and Ancillary Power from Storage

Economic to store up to 14% of the cheap Renewable Energy as dispatchable backup

Big grid-scale and small ‘BM’ Batteries replace ‘spinning reserve’ for frequency control

Concentrating Solar Thermal with Molten Salt Storage (*Tonopah, Nevada*)

Pumped Ocean Hydro (*3,400 ha. Ludington, L Michigan*)

Transition pathway to 100 % RE on the SWIS:

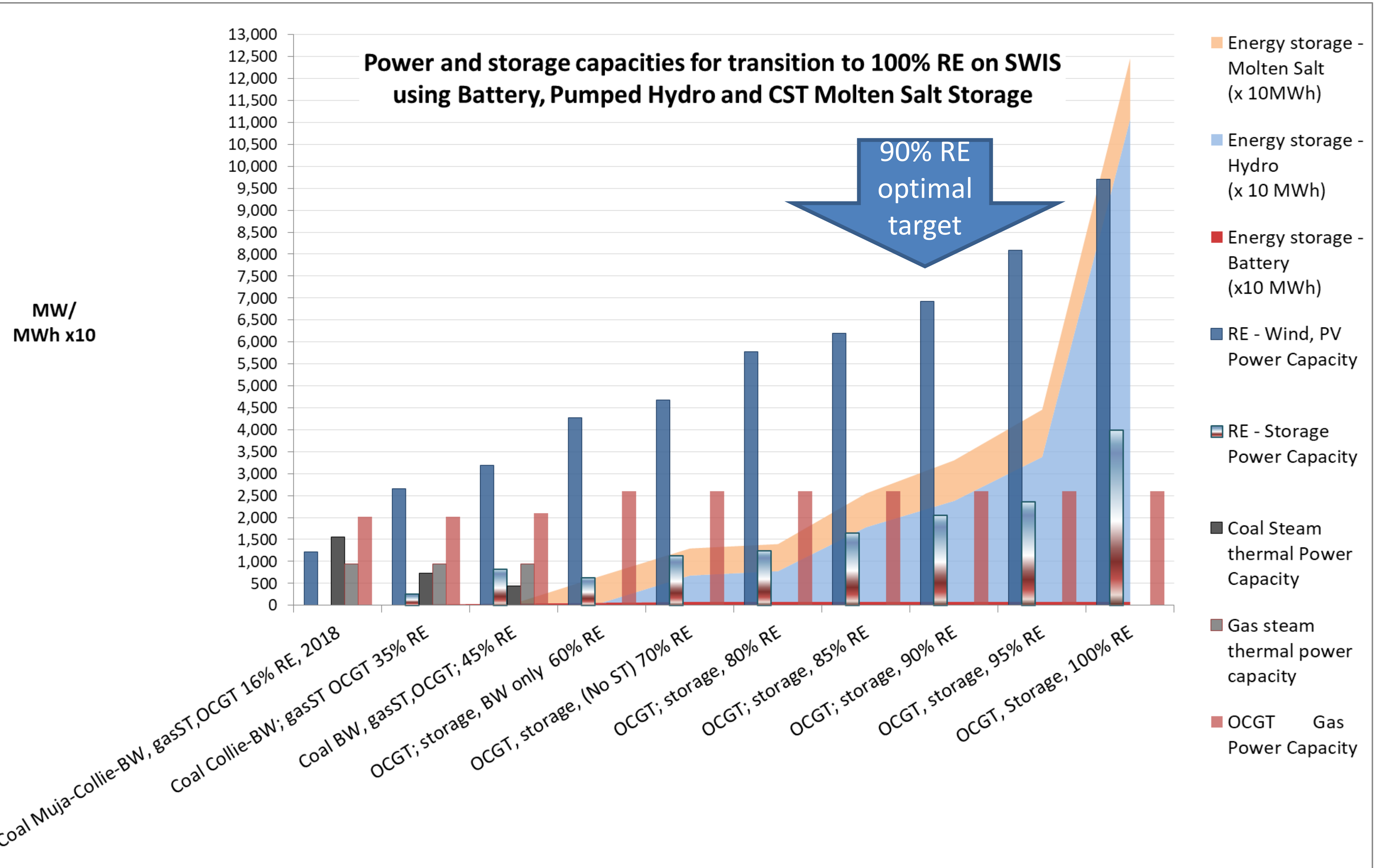
- Best with 3 types of storage – Battery, PHS and CST-MS.

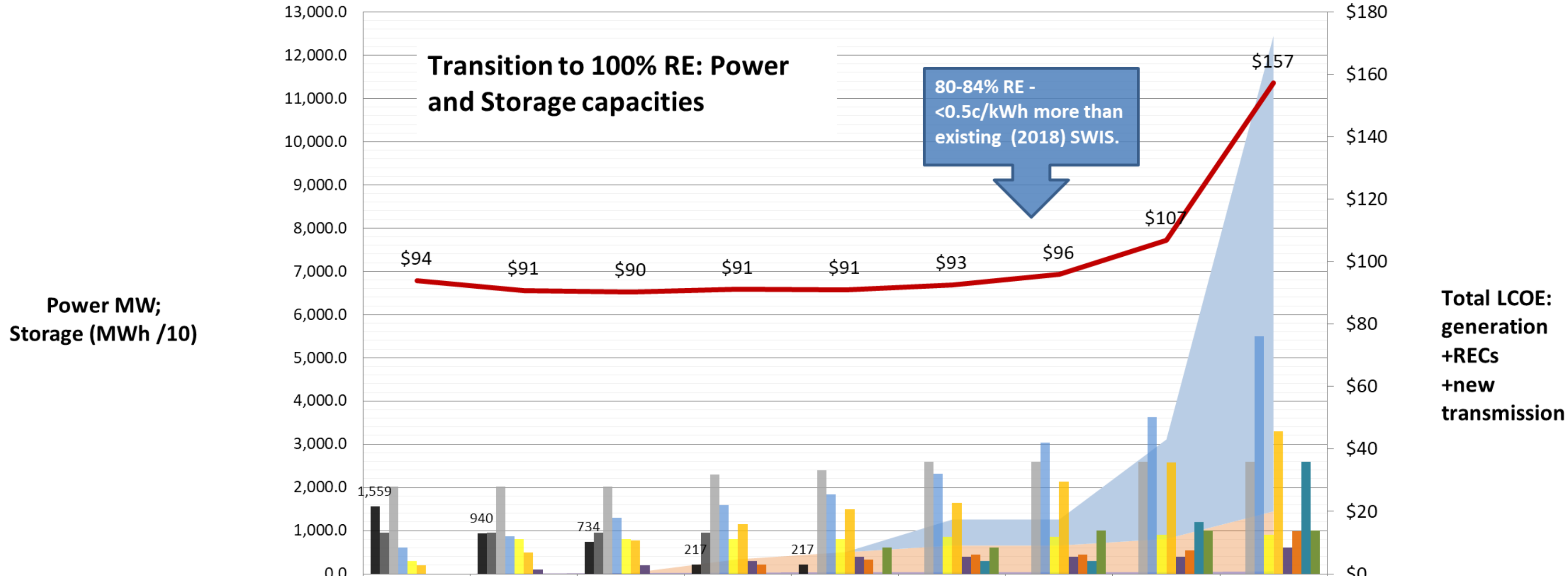
- For the 90% RE scenario modelled here - 14% of generation is renewable energy through CST – molten salt and pumped hydro storage.

- Renewable biofuel or hydrogen can be used to fuel the fast gas turbines (OCGT's) and or H_2 fuel cells for the remaining 10% to reach 100% RE.

- Renewable fueled OCGT's will cost less and be more practical than expanding storage to reach 100% RE.

What is the optimal target for wind, solar and storage?

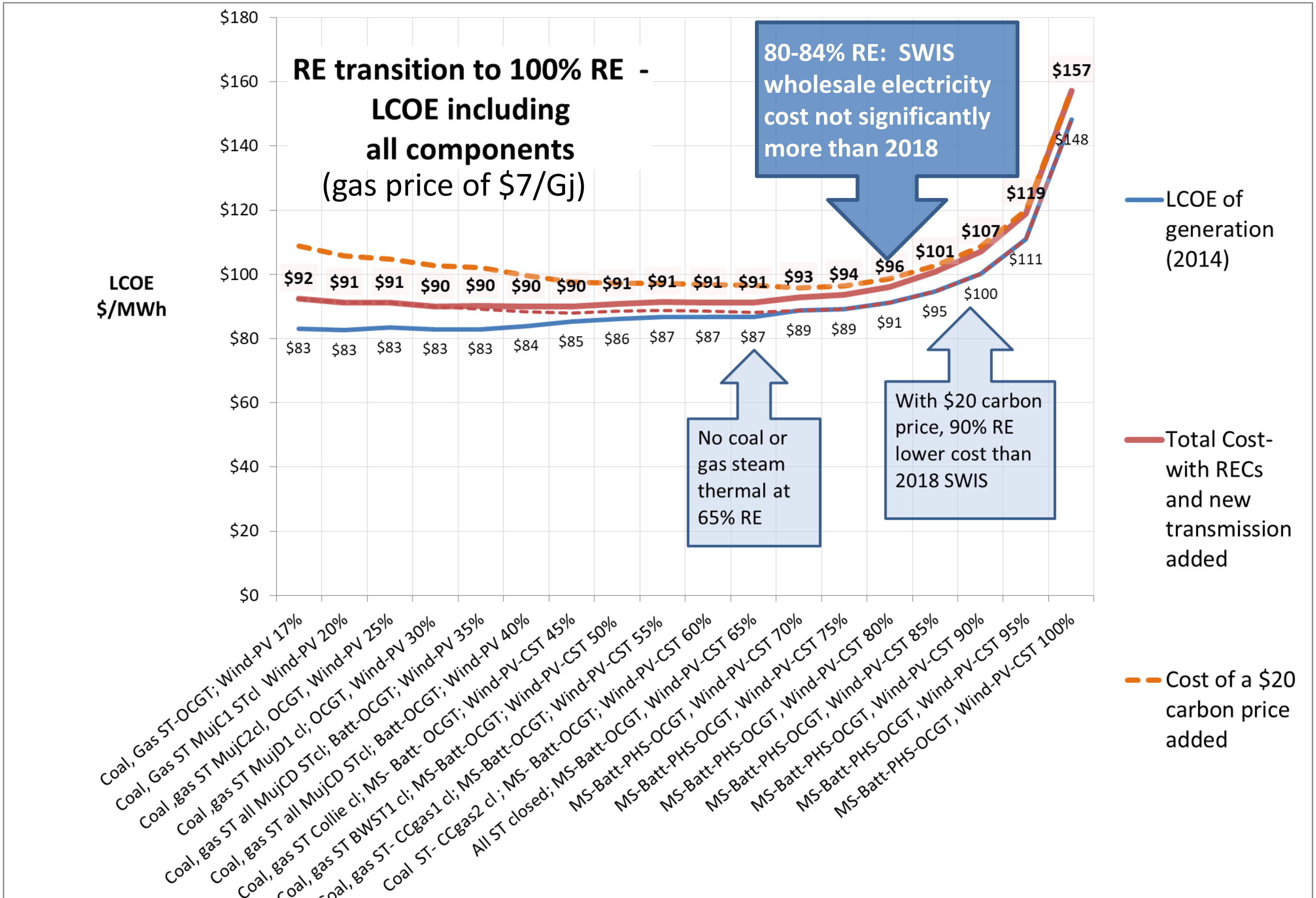

Power and storage capacities for transition to 100% RE on SWIS using Battery, Pumped Hydro and CST Molten Salt Storage
MW/ MWh x10
13,000
12,500
12,000
11,500
11,000
10,500
10,000
9,500
9,000
8,500
8,000
7,500
7,000
6,500
6,000
5,500
5,000
4,500
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
0
90% RE optimal target
Coal Muja-Collie-BW, gasST,OCGT 16% RE, 2018
Coal Collie-BW; gasST OCGT 35% RE
Coal BW, gasST,OCGT; 45% RE
OCGT; storage, BW only 60% RE
OCGT, storage, (No ST) 70% RE
OCGT; storage, 80% RE
OCGT; storage, 85% RE
OCGT; storage, 90% RE
OCGT, storage, 95% RE
OCGT, Storage, 100% RE
Energy storage - Molten Salt (x 10MWh)
Energy storage - Hydro (x 10 MWh)
Energy storage - Battery (x10 MWh)
RE - Wind, PV Power Capacity
RE - Storage Power Capacity
Coal Steam thermal Power Capacity
Gas steam thermal power capacity
OCGT Gas Power Capacity



	Coal, Gas ST-OCGT; Wind-PV 17%	Coal ,gas ST MujD1 cl; OCGT, Wind-PV 30%	Coal, gas ST all MujCD STcl; Batt-OCGT; Wind-PV 40%	Coal, gas ST BWST1 cl; MS-Batt-OCGT; Wind-PV-CST 50%	Coal ST-CCGT2 cl ; MS- Batt-OCGT; Wind-PV-CST 60%	MS-Batt-PHS-OCGT, Wind-PV-CST (no ST) 70%	MS-Batt-PHS-OCGT, Wind-PV-CST 80%	MS-Batt-PHS-OCGT, Wind-PV-CST 90%	MS-Batt-PHS-OCGT, Wind-PV-CST 100%
Hydro storage (MWh*10)	0	0	0	0	0	600	600	2,300	11,000
Molten Salt storage (MWh*10)	0	0	0	308	462	616	616	770	1,386
Batt storage (MWh*10)	0	10	20	30	40	40	40	40	60
Coal Thermal (MW)	1,559	940	734	217	217				
Gas CCGT/ cogen (MW)	945	945	945	945					
Gas OCGT fast ramping (MW)	2,019	2,019	2,019	2,300	2,400	2,600	2,600	2,600	2,600
Wind (MW)	600	870	1,305	1,590	1,840	2,310	3,040	3,620	5,500
PV rooftop (additional to 400 MW in 2014)	300	800	800	800	800	850	850	900	900
PV tracking (MW)	190	495	780	1,150	1,490	1,640	2,140	2,570	3,300
Battery (MW)	0	100	200	300	400	400	400	400	600
Conc. Solar Thermal (MW)	0	0	0	220	330	440	440	550	990
Pumped Hydro (MW)	0	0	0	0	0	300	300	1,200	2,600
Demand side management (DSM)	0	0	0	0	600	600	1,000	1,000	1,000
Total Cost- with RECs and new transmission added	$94	$91	$90	$91	$91	$93	$96	$107	$157

- 90% RE is a sensible target in terms of cost and physical constraints.
- There are many combinations of wind, solar and storage that will do the job
- Remaining 10% from OCGT's and or fuel cells fueled by H_2 and or bio-fuels → 100% RE.

What will the transition to renewable electricity cost?


RE transition to 100% RE -
LCOE including
all components
(gas price of $7/Gj)
80-84% RE: SWIS wholesale electricity cost not significantly more than 2018
No coal or gas steam thermal at 65% RE
With $20 carbon price, 90% RE lower cost than 2018 SWIS
LCOE $/MWh
$180
$160
$140
$120
$100
$80
$60
$40
$20
$0
$92 $91 $91 $90 $90 $90 $90 $91 $91 $91 $91 $93 $94 $96 $101 $107 $119 $157
$83 $83 $83 $83 $83 $84 $85 $86 $87 $87 $87 $89 $89 $91 $95 $100 $111 $148
Coal, Gas ST-OCGT; Wind-PV 17%
Coal, Gas ST MujC1 STcl Wind-PV 20%
Coal ,gas ST MujC2cl, OCGT, Wind-PV 25%
Coal ,gas ST MujD1 cl; OCGT, Wind-PV 30%
Coal, gas ST all MujCD STcl; Batt-OCGT; Wind-PV 35%
Coal, gas ST all MujCD STcl; Batt-OCGT; Wind-PV 40%
Coal, gas ST Collie cl; MS- Batt- OCGT; Wind-PV-CST 45%
Coal, gas ST BWST1 cl; MS-Batt-OCGT; Wind-PV-CST 50%
Coal, gas ST- CCgas1 cl; MS-Batt-OCGT; Wind-PV-CST 55%
Coal ST- CCgas2 cl ; MS- Batt-OCGT; Wind-PV-CST 60%
All ST closed; MS-Batt-OCGT, Wind-PV-CST 65%
MS-Batt-PHS-OCGT, Wind-PV-CST 70%
MS-Batt-PHS-OCGT, Wind-PV-CST 75%
MS-Batt-PHS-OCGT, Wind-PV-CST 80%
MS-Batt-PHS-OCGT, Wind-PV-CST 85%
MS-Batt-PHS-OCGT, Wind-PV-CST 90%
MS-Batt-PHS-OCGT, Wind-PV-CST 95%
MS-Batt-PHS-OCGT, Wind-PV-CST 100%
LCOE of generation (2014)
Total Cost- with RECs and new transmission added
Cost of a $20 carbon price added

1. 70% RE - all steam thermal closed, electricity cost $93/MWh - same as existing (2018) electricity with no carbon price.

2. 80-85% RE – $96 MWh – only 0.4 c/ kWh more than 2018 cost.

3. With a low ($20) price on CO2, existing electricity would cost $110- $115.
   - 90-95% RE would cost >1c / kWh less- $108-110/ MWh.
   - In other words a $20 C price deliver an additional 10% RE.

What about gas cost?

- Gas price of $9/ GJ increases LCOE by $5-6/ MWh compared to the modelled price of $7/GJ, during early to mid-transition.
- Cost relativities outlined in the previous slide are not affected by the higher gas price.
- Annual gas use will increase during the transition and declines to about 50% of current levels at 90% RE.

How much RE is needed to replace coal and gas steam thermal and how much will this cost?

A modelled scenario with enough renewable power and storage to replace existing - 2,500 MW of coal and gas ST + 2,000 MW OCGT's.

Power Capacity (MW)								Storage Capacity (MWh)		
Gas OCGT fast ramping	Wind	PV rooftop (additional to 400 MW in 2014)	PV tracking	Battery	Conc. Solar Thermal	Pumped Hydro	Demand side manage-ment (DSM)	Battery storage	Molten Salt storage	Hydro storage
2,600	**2,020**	**800**	**1,690**	**400**	**440**	**0**	**600**	**800**	**6160**	**0**

- **5,350 MW RE** power – 2020 MW of wind, 1690 MW of solar tracking PV, 1200 MW of rooftop PV and 440 MW of solar CST.
- **2,600 MW OCGT** power – new fast ramping gas units
- **6160 MWh RE storage (battery and CST MS)**
- **Generates 65% renewable energy; balance from OCGT's**

Replacing all coal and gas steam thermal plant with RE power to generate 65% renewable electricity :

- **Likely to reduce wholesale electricity prices slightly compared to existing (2018).**
- $90 - $97/ MWh for gas prices of $7 - 9 per GJ

Does coal or gas steam thermal have a future with renewables?

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Renewables slash use of coal

DANIEL MERCER

Synergy's coal-fired power stations have been running below capacity because of green power surges. Picture: Sharon Smith

Coal-fired power plants operated by State-owned power provider Synergy are running at as little as one-third of their capacity amid the onslaught of renewable energy flooding WA's main electricity grid.

In a sign of the financial pain being inflicted on its traditional thermal generation business, Synergy said the 340MW Collie power station ran at just 34 per cent of its capacity in January.

Figures show none of the utility's three coal-fired generators of Collie, Muja C and Muja D ran anywhere near its capacity in the three months to February 28, despite demand for power typically peaking in summer.

Across the period, the 390MW Muja C unit had a "capacity factor" of 53 per cent in December, 59 per cent in January and 43 per cent in February, while the 422MW Muja D operated at capacity of 38 per cent, 53 per cent and 65 per cent.

By contrast, the Japanese-owned Bluewaters power station, which has take-or-pay contracts with customers including Synergy, ran at up to 90 per cent during the period.

The data show the extent to which Synergy's business is being buffeted by surging levels of green power in the South West interconnected system, led by rooftop solar, of which about 1000MW has been installed.

It also coincided with a report from the Australian Energy Market Operator which said Synergy faced big increases in costs as its coal-plants were increasingly stopped and started to cope with the influx of renewable energy.

AEMO also noted that stopping and starting coal plants increased the risk of units tripping in the run-up to the evening peak when solar power tapered off, potentially leaving consumers vulnerable. With cheap renewable energy flooding the system at various times of the day, Muja and Collie are increasingly being pushed out of the market.

Chiefly responsible is solar power, which is now the biggest single source of electricity when aggregated and often sends daytime wholesale prices crashing.

But Synergy is also exposed at night, when output from wind turbines is typically highest and demand for electricity is low.

This has forced Synergy to ramp its coal plants up and down to accommodate the ebbs and flows of renewable power, hurting their ability to run as "baseload" operations.

Synergy said the trend was not only reducing revenue by cutting into the operating capacity of its plants, but also leading to increased maintenance costs as the units were run outside of their design specifications.

A Synergy spokeswoman said cycling the utility's coal-fired plants also led to "an increased risk of unplanned outages due to deterioration of (the) plant".

Maintenance and capital costs of old coal power stations used in ramping (cycling) mode have been modelled as rising to 2 -4 times the costs for normal baseload mode

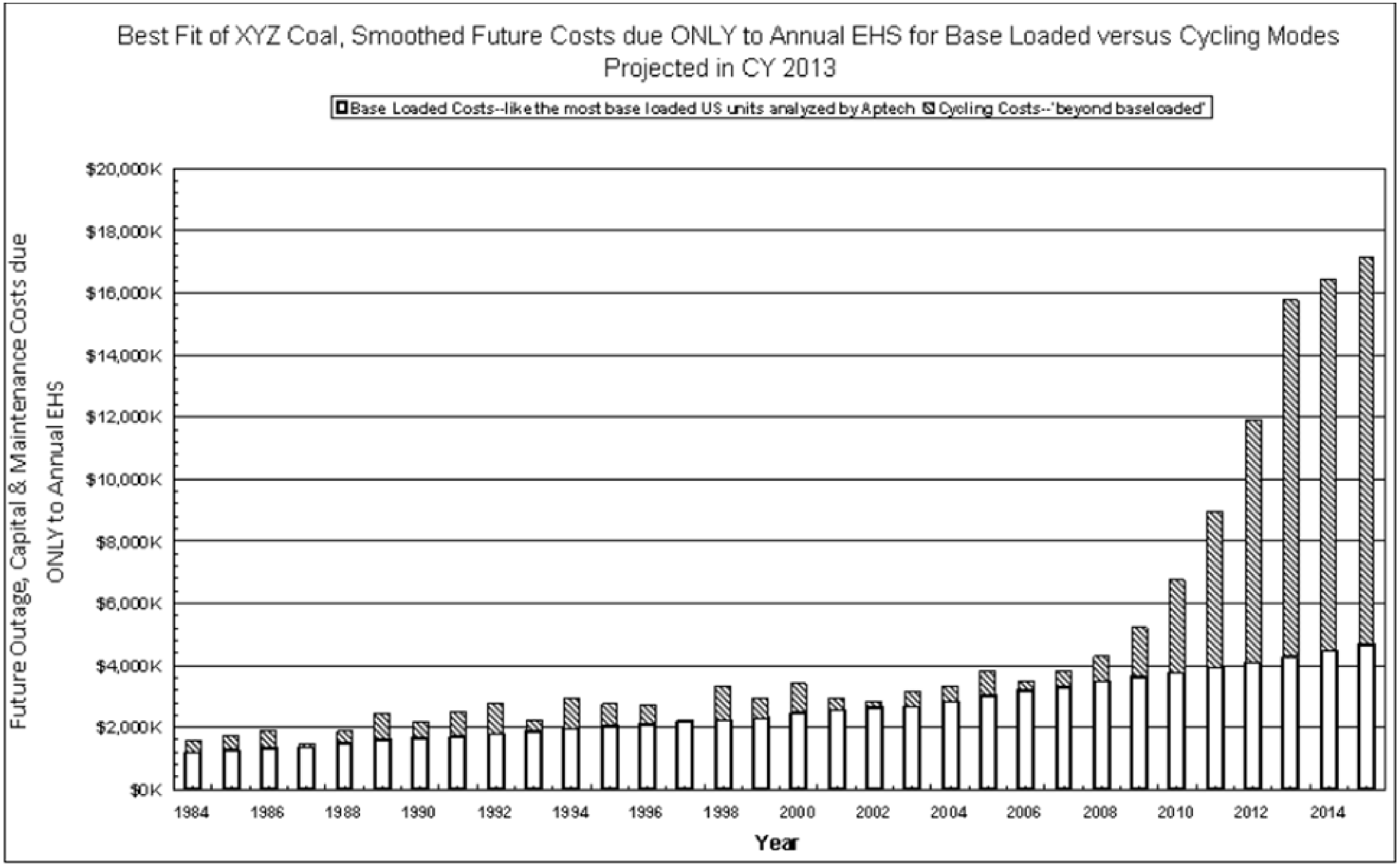


Figure B-7: Best Estimate of XYZ Cycling Maintenance and Capital Costs.

Ref: NREL, April 2012. *Power Plant Cycling Costs.* N. Kumar, et al

EXAMPLE ILLUSTRATING THE EFFECT OF R.E. ON STEAM THERMAL RAMPING

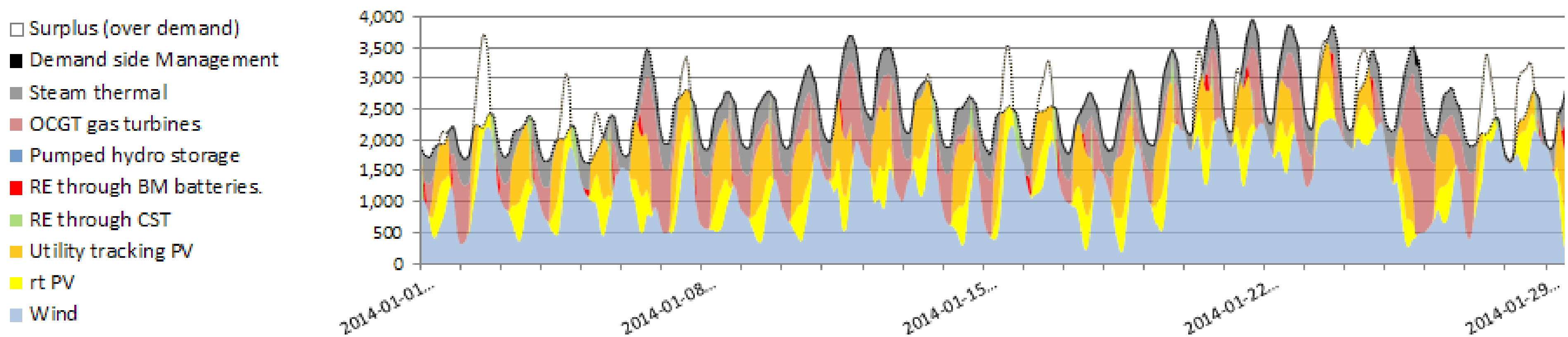
Fuelled energy: Blue Waters coal Steam Thermal 434 MW; Fast gas turbines 2300MW

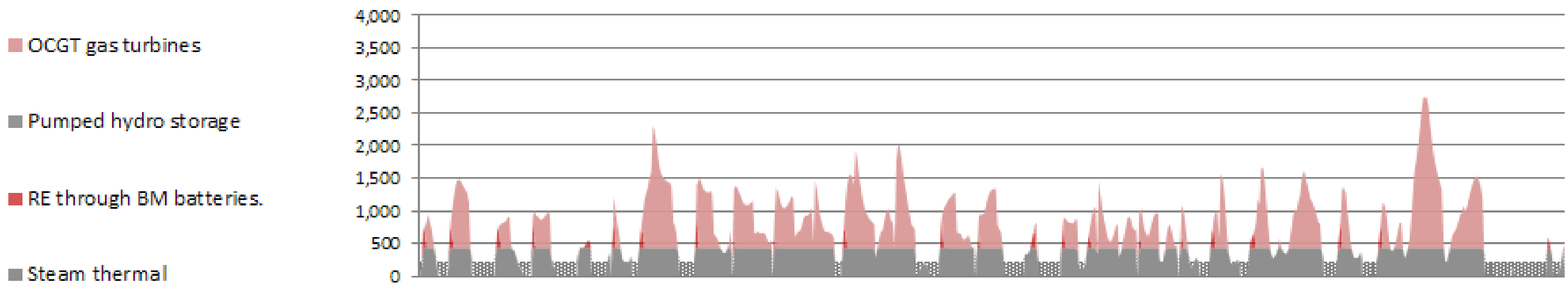
Renewable Energy capacity : Wind 2700MW, PV 1880 MW (+300 MW rooftop, 2014).

Storage: 600 MWh of batteries.

Renewable Energy generation: 60%.

Modelled using summer 2014 weather and load data





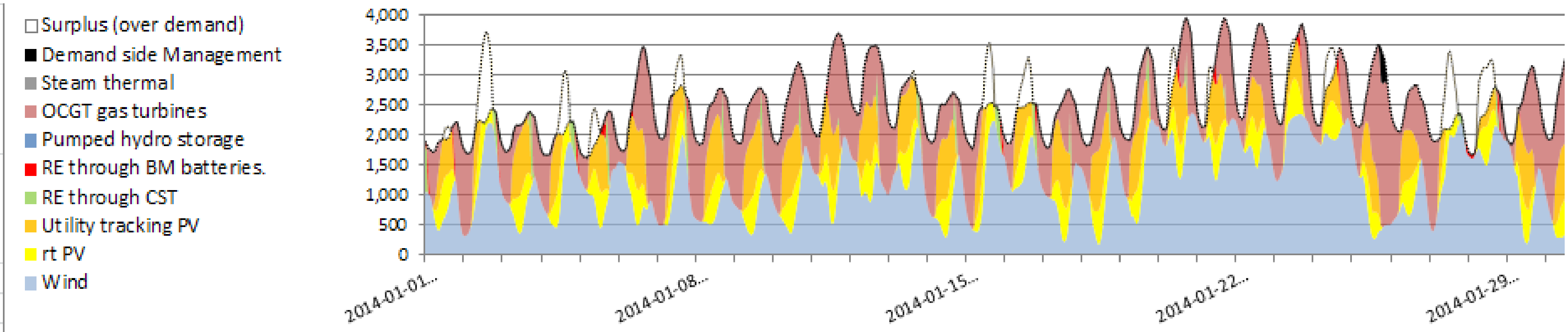
'Unnecessary' steam thermal generation is stippled grey in lower graph

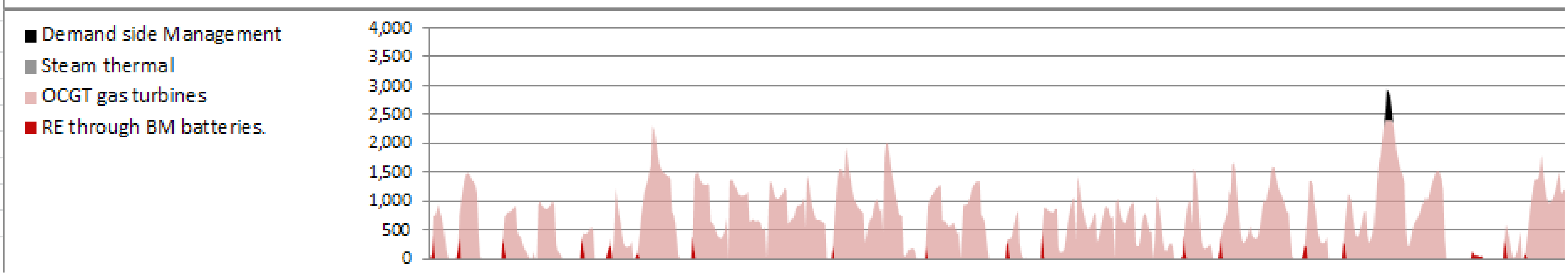
Fuelled capacity: No coal or gas as ST; 2400 MW fast ramping OCGT's.

Renewable Energy capacity and storage as for previous slide

Renewable Energy generation: 64%

Summer 2014 data



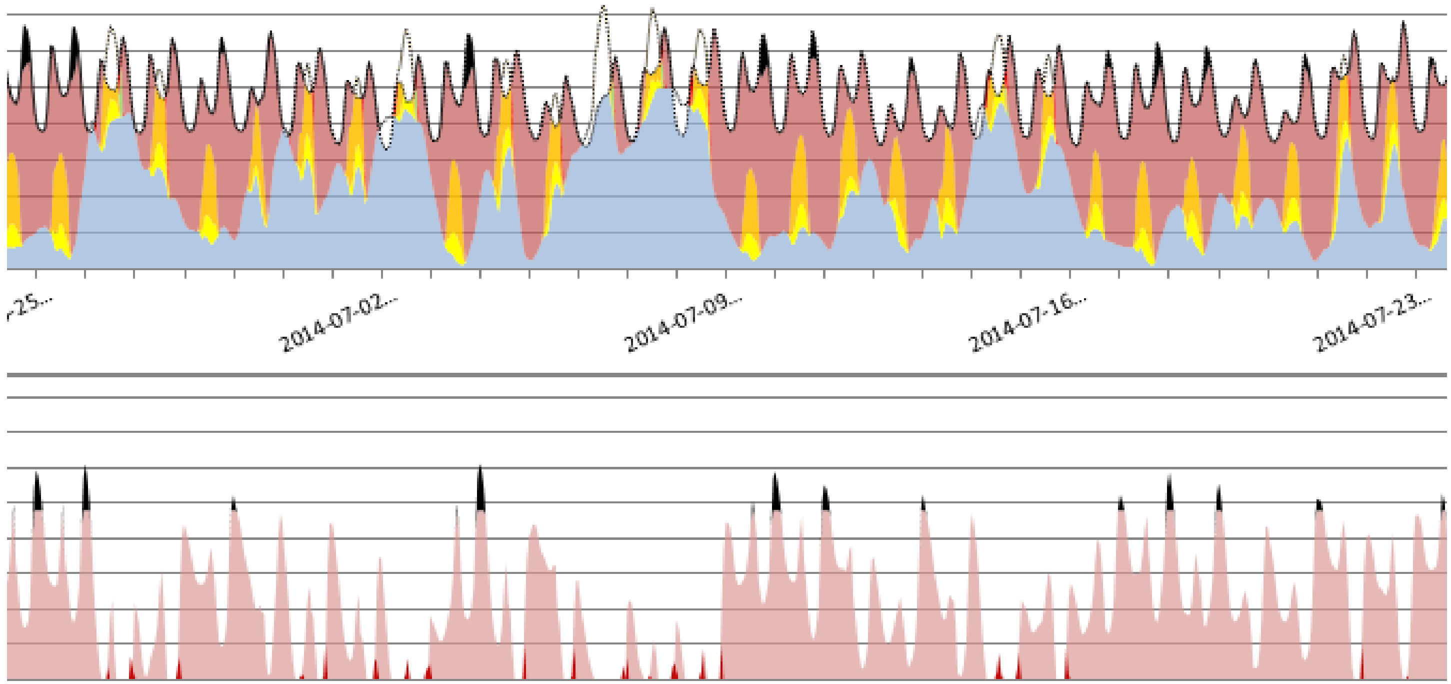


The solution: Replace coal and gas ST with wind and solar as rapidly as possible. Use OCGT's, storage and DSM to back up RE

All power capacities as for previous slide

Renewable Energy generation: 64%

Winter 2014 data



The solution –replace coal and gas ST with wind and solar ASAP – use OCGT's, storage and DSM backup

Transition stage/ Percent Renewable Energy	Capacity (MW) of coal and gas steam thermal ('baseload power')	Number of hours where Steam Thermal needed is < 30% ST capacity	Number of Steam thermal ramps >33% of max. ST capacity per hour	Surplus Steam Thermal (% of 'baseload energy')
WPV-C-CCGT-GFR (1) 2018 17%	2,504	447	0	0.0%
WPV-C-CCGT-GFR (2)MujC1 STcl 20%	2,298	416	0	0.0%
WPV-C-CCGT-B-GFR (3)MujC2 STcl 25%	2,092	706	0	0.0%
WPV-C-CCGT-B-GFR (4)MujD1 STcl30%	1,885	1,045	23	0.3%
WPV-C-CCGT-B-GFR (5)MujCD STcl 35%	1,679	1,342	70	0.9%
WPV-C-CCGT-B-GFR (6) no closure 40%	1,679	1,880	114	2.0%
WPV-C-CCGT-B-GFR (7 CollSTcl 45%	1,379	1,751	162	2.8%
WPV-CCGT-B-GFR (8) BWST1 cl 50%)	1,162	1,980	240	4.4%
WPV-CCGT-B-GFR (9) GST1 cl 55%	690	1,840	327	5.4%
WPV-CCGT-B-GFR (10) GST2 cl 60%	217	1,808	371	6.6%
WPV-CCGT-B-OCGT(11) all STcl 65%	0	0	0	0.0%
OCGT, storage, 70% RE	0	0	0	0.0%

To minimize excessive ramping of steam thermal, install RE rapidly, closing ST generators as RE capacity increases. Close all ST before RE generation reaches 65-70%. Switch to fast-ramping OCGT plus storage as backup

Fast ramping Open Cycle Gas Turbines

Provide 2 - 40% of energy during transition to RE

- **Ramp from cold start to full load in 6 – 13 minutes.**
- Located In Metro and industrial areas.
- 1 in 6 can be equipped to run as 'synchronous compensators' for frequency control

- Energy cost $110 - $300 / MWh depending on hours run,
- Can use many fuels – gas, bio-oil,

Summary:

- Coal and gas steam thermal (ST) do not function well as backup for renewables because faster ramping and more shut-downs / start-ups will increase cost and decrease reliability of the ST generators.

Damage to ST generators can be reduced by:

1. Increasing maintenance and replacement of parts
2. Paying to curtail wind and solar, which has zero marginal cost.

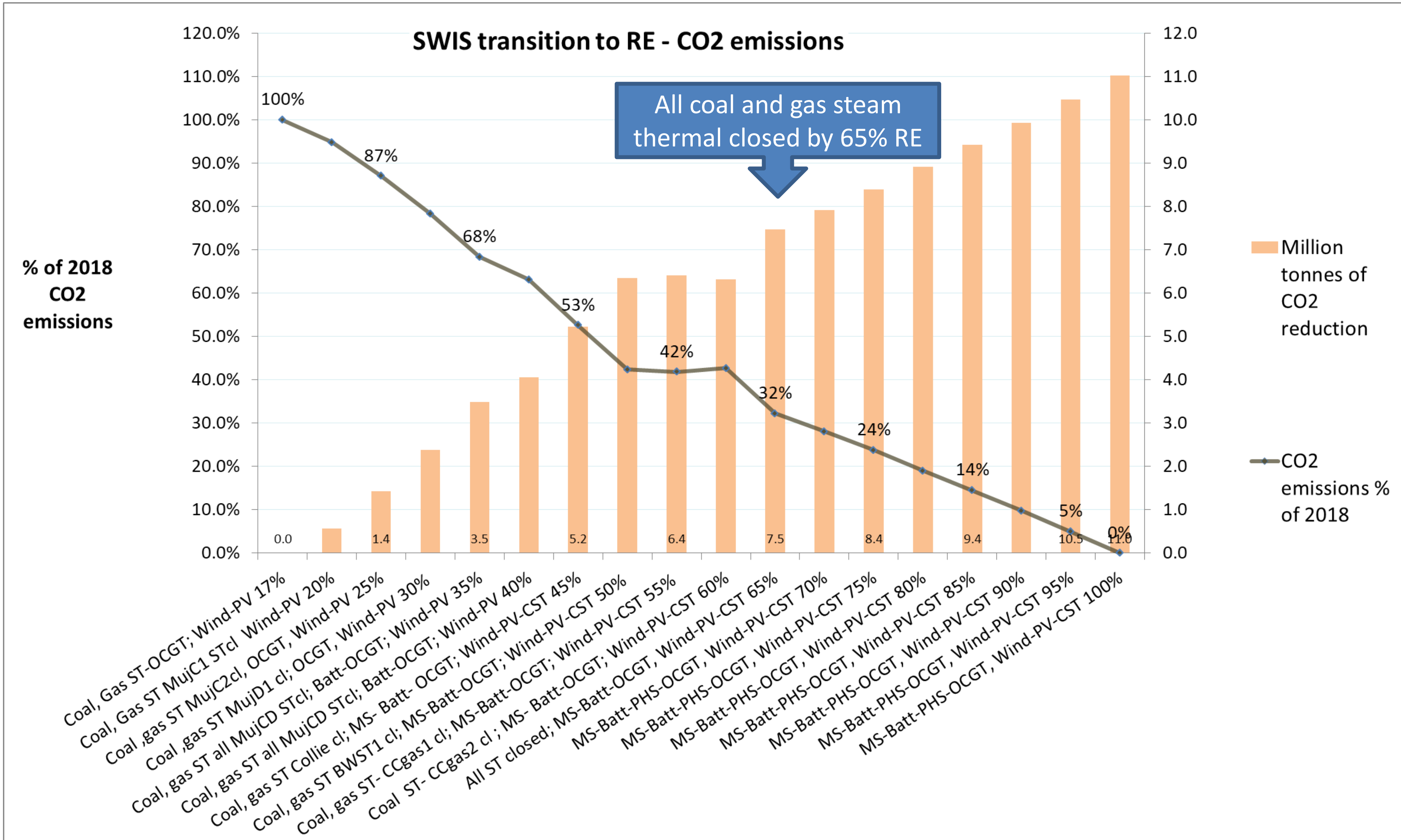
CONCLUSIONS

1 & 2 above push up LCOE of coal and gas steam thermal (ST) and make it less reliable.

As RE increases, need to phase out the ST early. Replace with fast ramping OCGT's and storage by 65-70% RE.

But isn’t renewable energy mainly about reducing carbon emissions?

Closing all coal and gas ST reduces CO2 emissions by 7.5 million tonnes or 70%



OCGT= Gas fast response turbines ; ST =Steam thermal, B=Battery, Storage=molten salt and pumped hydro

Emissions comparison with installing new fossil fuel thermal plant

Ultra-supercritical black coal (HELE) may not even be practical on SWIS due to small scale of SWIS. If it were possible to replace current generation with new HELE and gas thermal units the result would be :

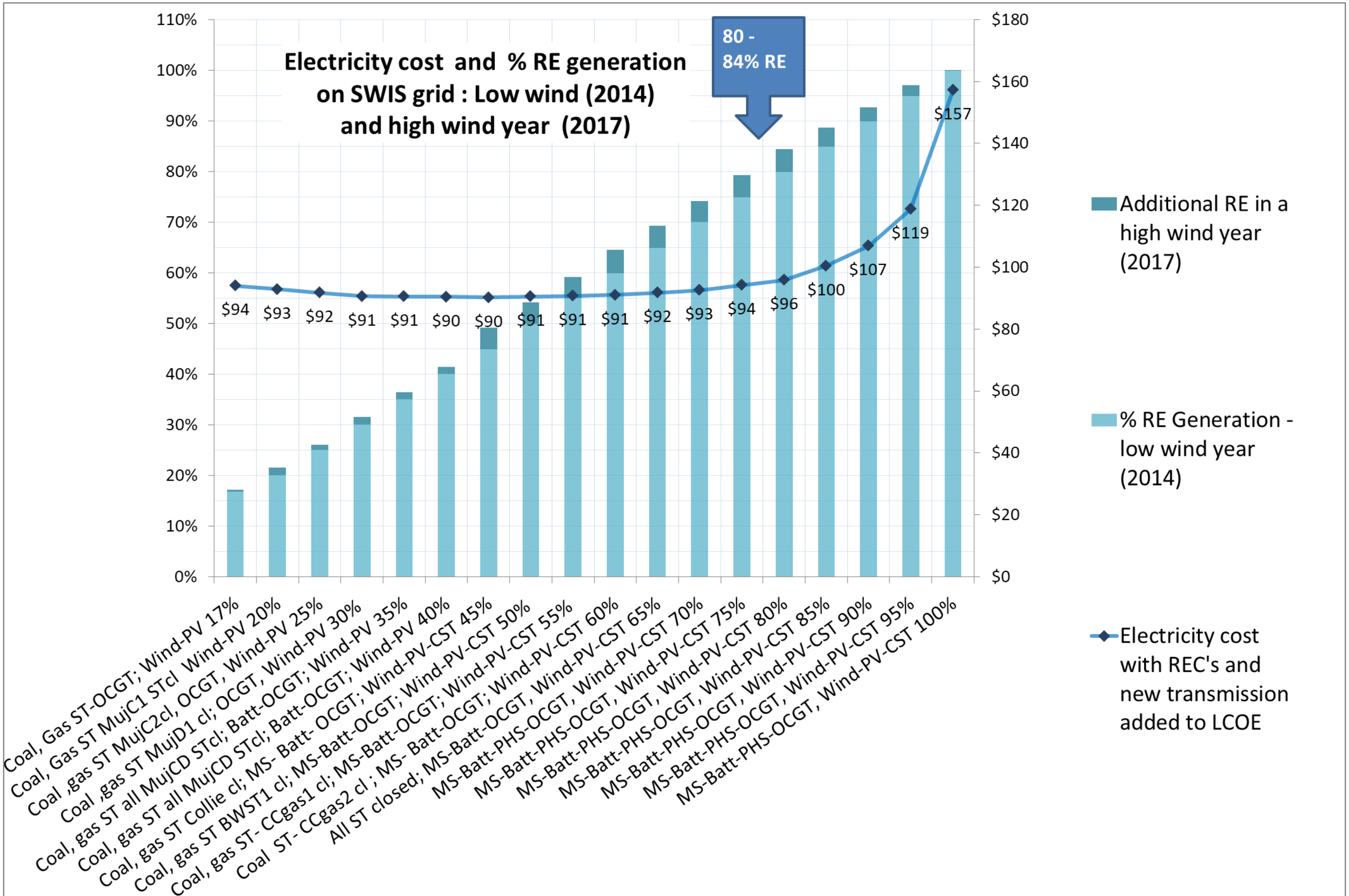
- CO_2 emissions set at 81% of 2018 SWIS levels for 30 years
- Electricity cost - $103-105/MWh – about the same as 85-90% RE
- **85-90% RE gives 70% less CO_2 emissions than HELE-gas for no more cost.**
- **Emissions can be reduced further by increasing percentage of renewables.**

Assumptions:

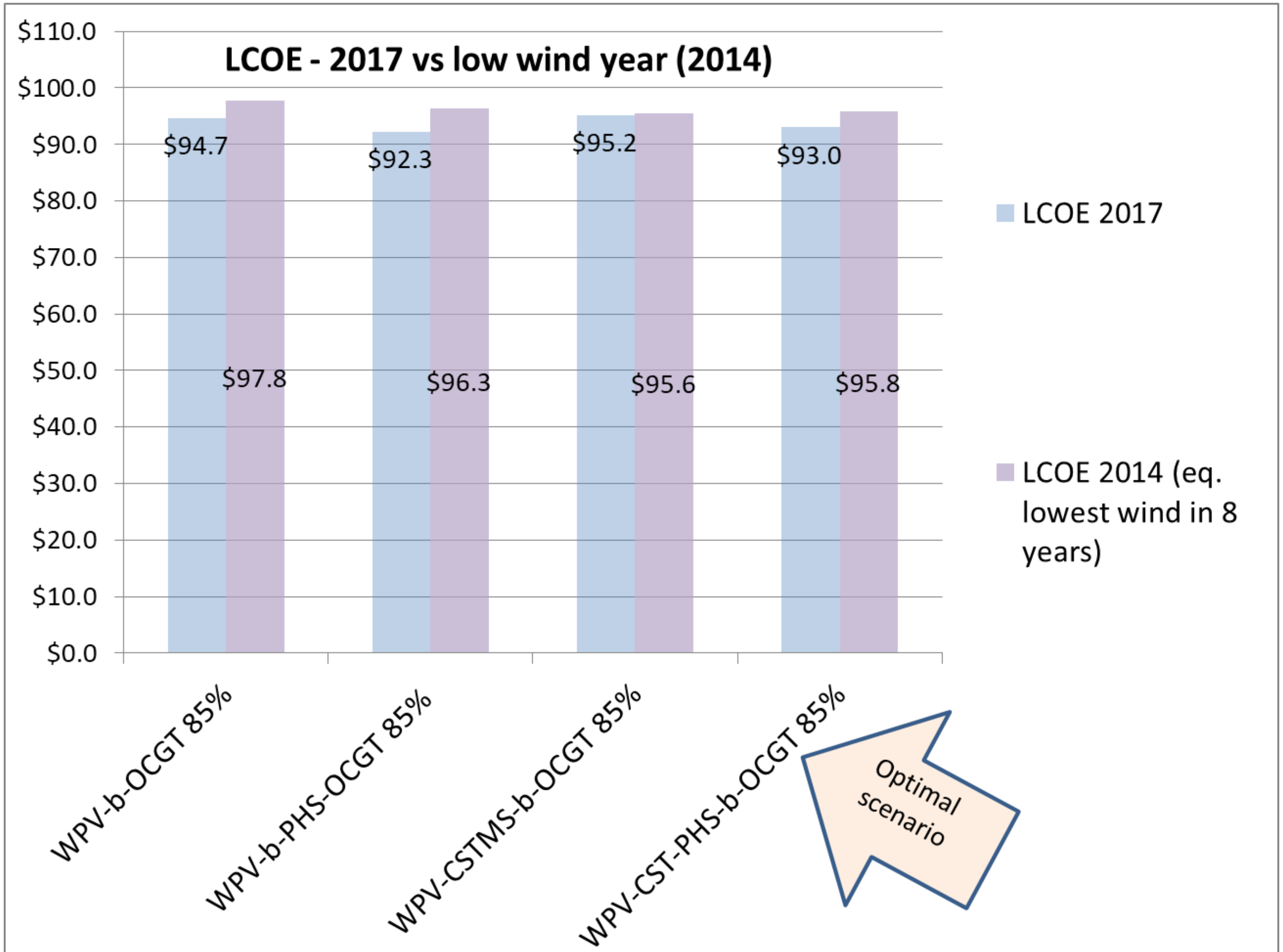
- *that capital for fossil fueled plants can be obtained for a WACC of 8%.*
- *HELE coal plant emission factor is 0.7 tCO_2e/ MWh compared to 0.92 for subcritical black coal.*
- *(ref: Climate Council, Finkel, 2016)*

How variable is renewable energy?

RE generation can vary up to 5% between good and bad wind years

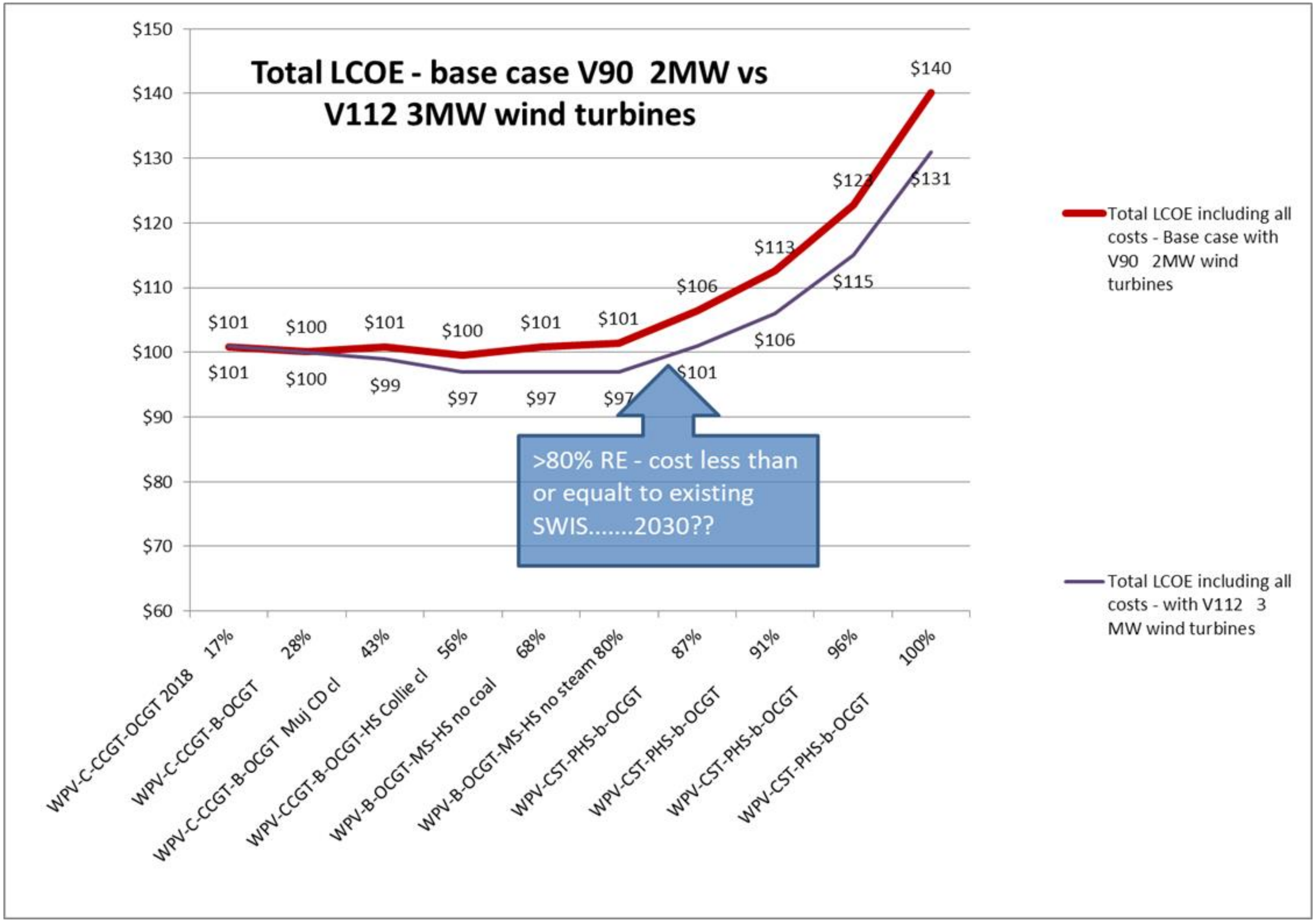


LCOE varies by up to 5% year on year due to variations in the wind and solar resources



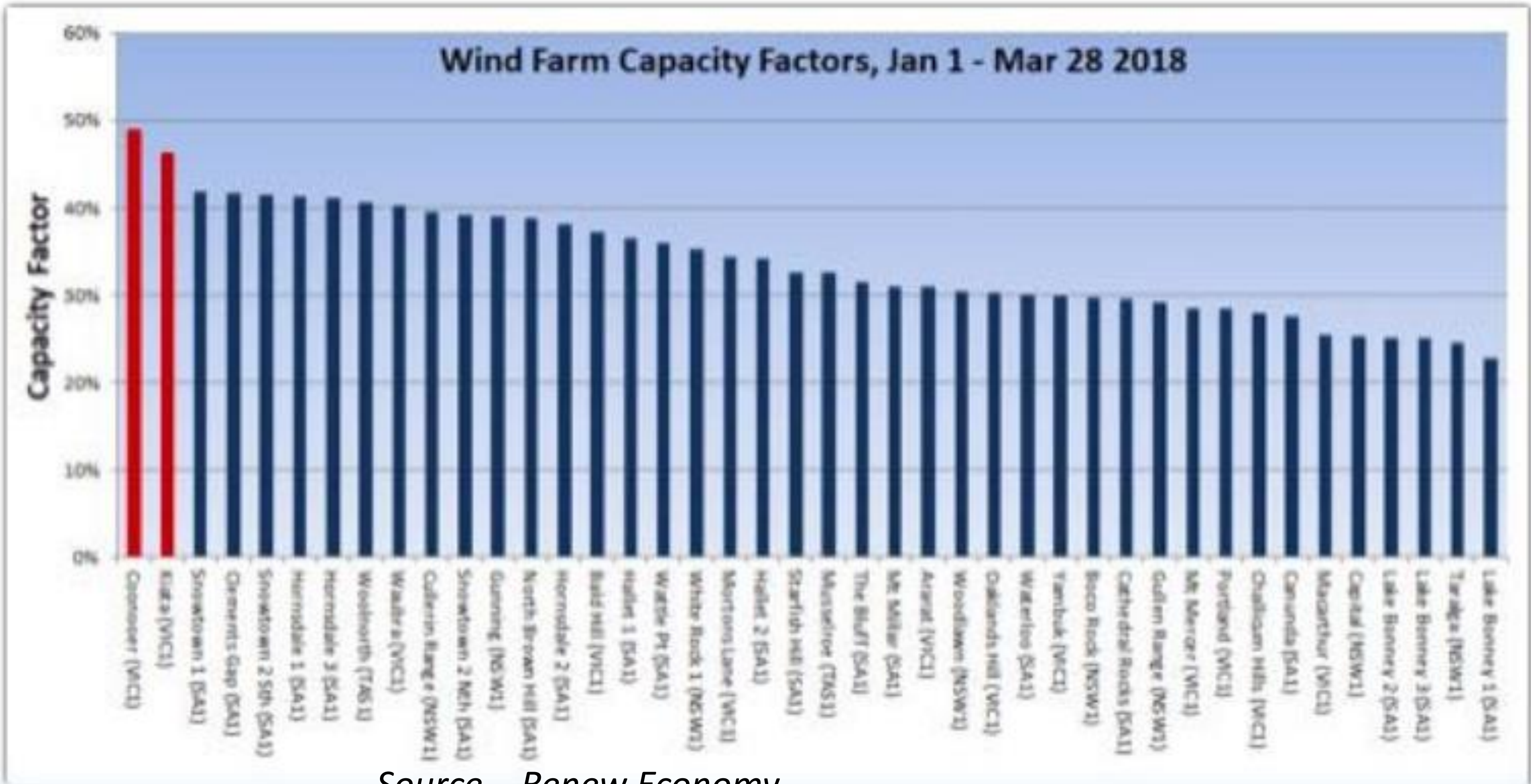
- LCOE in a good wind year (2017) is about 3 – 4 % less than in a low wind year (2014).
- High solar/CST scenarios are less affected

How and where can wind be most effective?

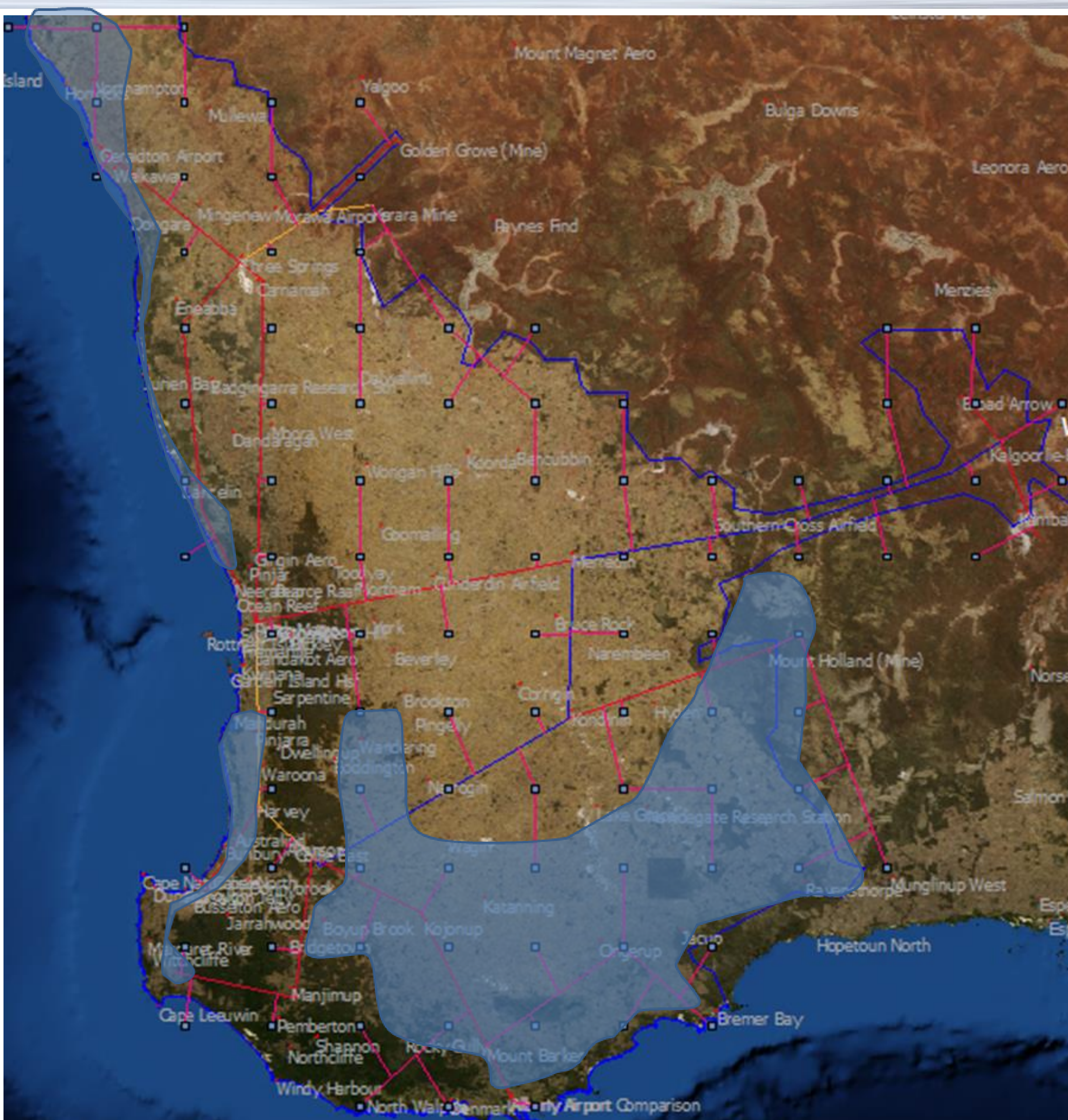


Modelling of LCOE using Vestas V112 3MW wind turbines decreases LCOE by up to 7% (purple line) compared to V90 2MW turbines (red), because electricity generation is higher in relation to capacity installed i.e. more efficient

#KiataWindFarm joins #CoonooerBridgeWindFarm at the front of the pack.
@Windlab's wind farms continue to be the highest performing on the #NEM



Source – Renew Economy



Optimal areas for winter wind

Windiness - 100 cell grid over SWIS

Year	% of average
2017	107.5%
2016	107.9%
2015	93.2%
2014	93.9%
2013	94.8%
2012	97.5%
2011	100.4%
2010	93.5%
2009	103.4%
2008	104.7%
2007	110.6%

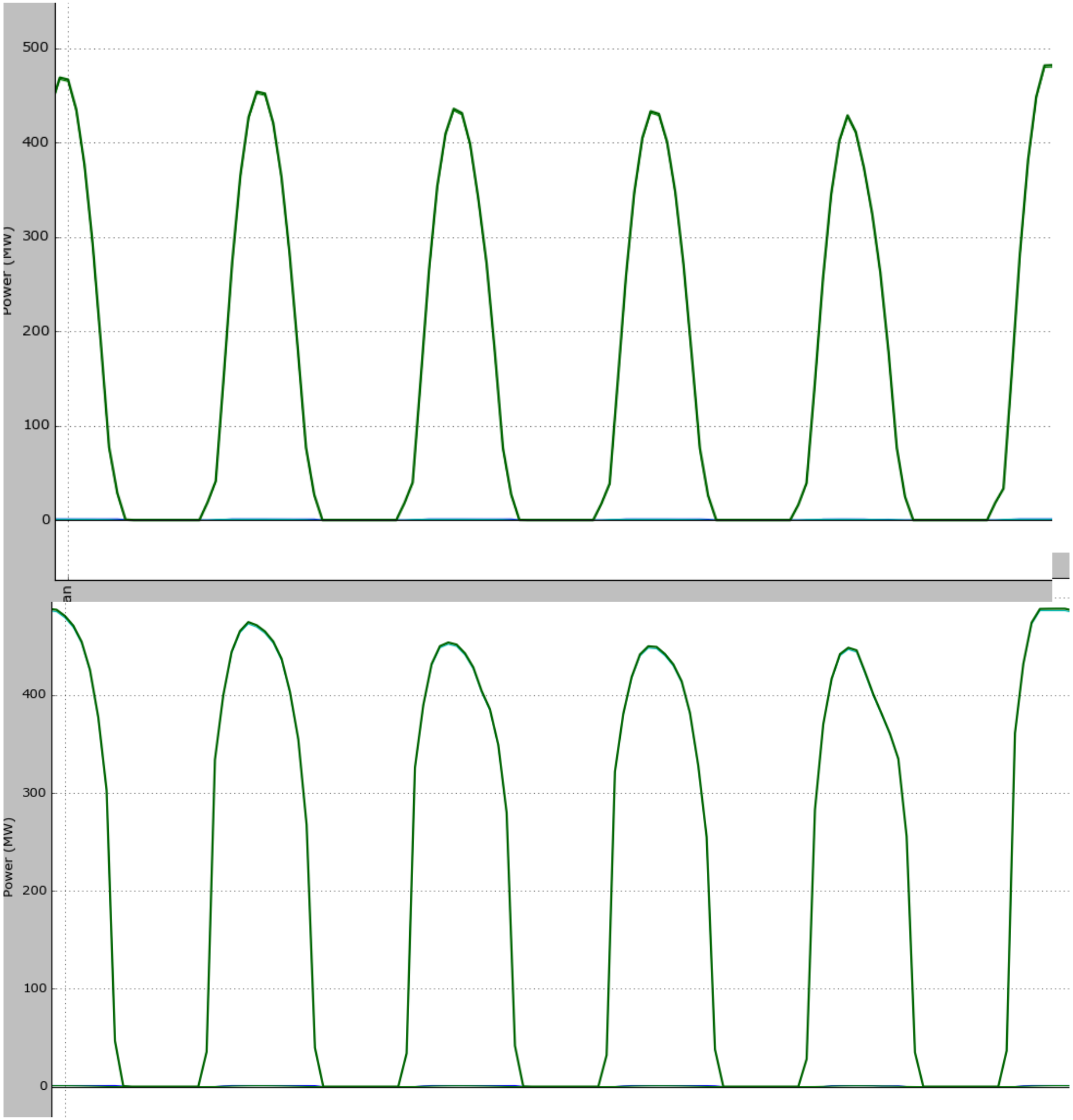
11 years - variation of minus 7% to plus 11% of average year

1. Wind power is a major portion of the most cost-optimal RE scenarios –50 – 70% of all energy generated.
2. Newer and bigger is best
   - Turbines getting bigger (3 – 7 MW)
   - More efficient - capacity factors near 50% - lower LCOE.
   - Storm rated 200 km/ hr.
3. Location - location - location
   - Winter moderate wind performance needed (generation peaks usually surplus spilled)
   - Great Southern and West Coast best.
4. Annual 'windiness' of SW varies up to 20% annually.
5. LCOE affected much less - varies by only 5% annually
6. Low wind periods mainly autumn – winter, up to

What type of solar to use?

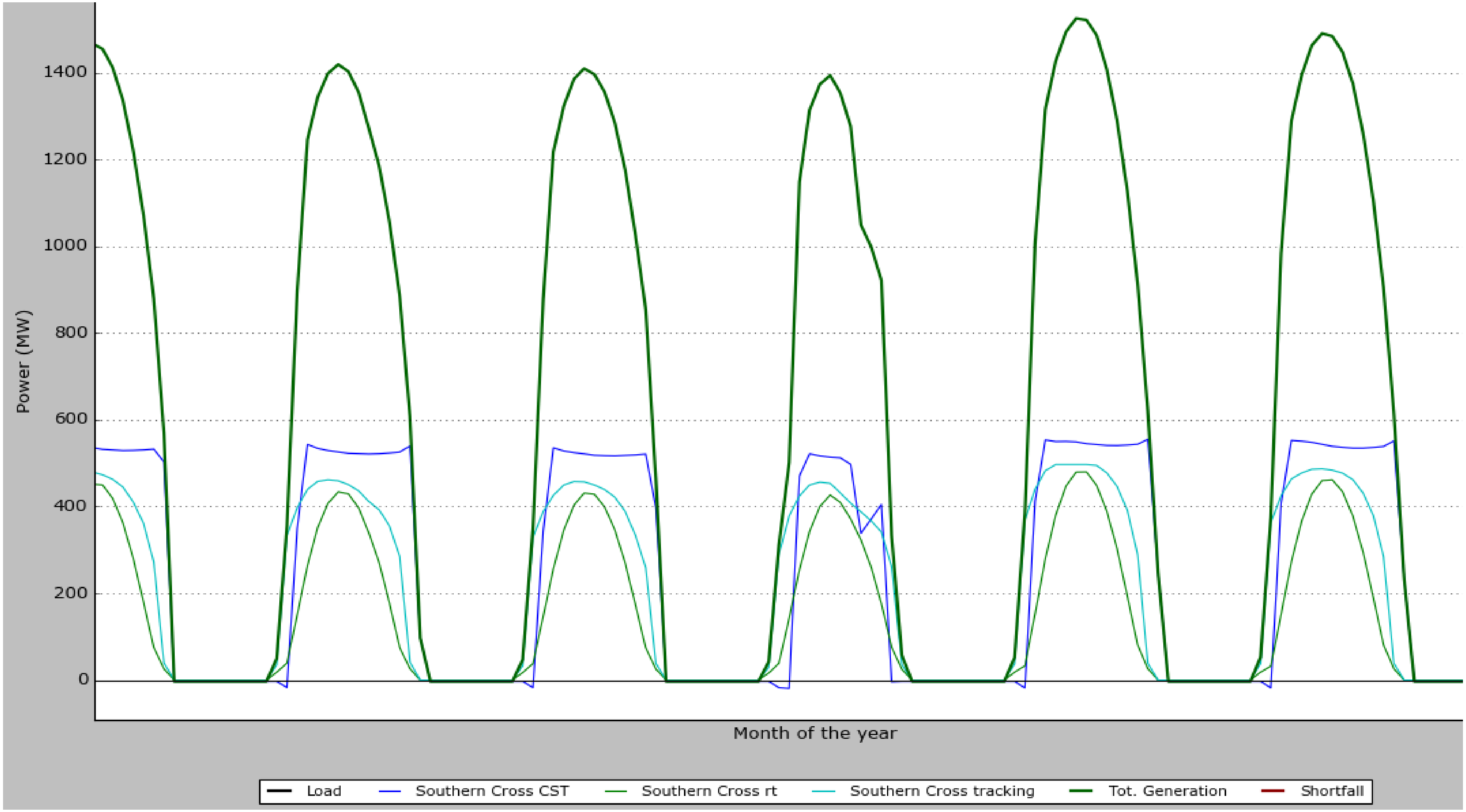
Fixed PV
CF = 21%

Fixed rooftop PV vs Tracking solar PV, (500 MW at same location) first 5 days of January 2017

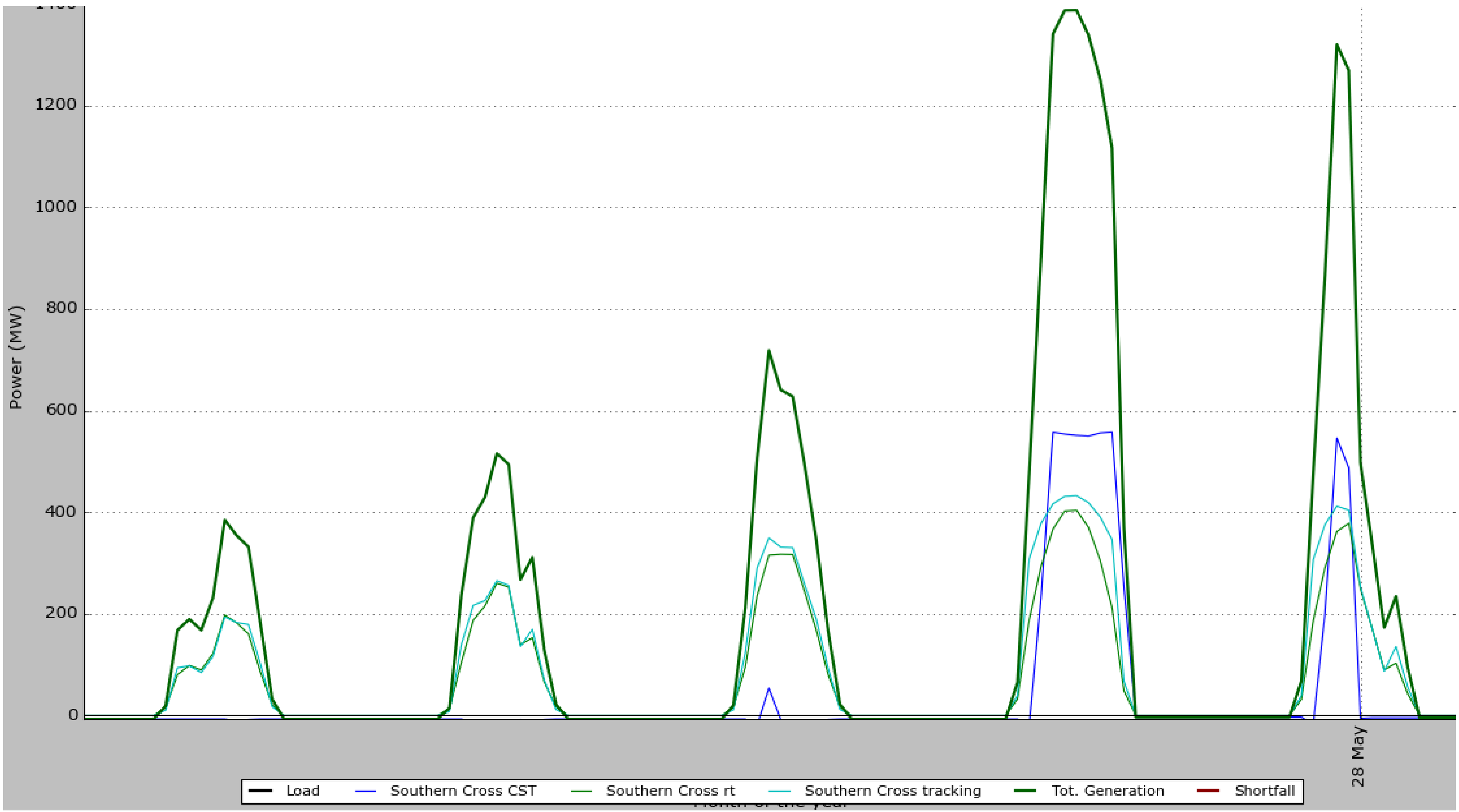


Tracking PV
CF = 31%

Fixed rooftop PV (thin green) vs Tracking solar PV (light blue) vs CST with 6 hour storage (dark blue). Thick green curve is total power. 500 MW each at same location, first 5 days of January 2017.



Technologies / capacities as for previous slide.
5 days to 28 May 2017.



3 TYPES OF SOLAR – SUMMARY POINTS

1. **All are cost effective and can contribute to a renewable SWIS grid**
2. **Under cloud cover, PV** still generates at a reduced rate while CST does not generate at all.
3. **Utility Tracking PV.** Compared to fixed rooftop PV, it:
   - Has better 'power spread'
   - Is less 'peaky'
   - Is more controllable
   - Has higher capacity factor (about 30% vs 19-21%)
4. **Rooftop PV**
   - Cheap, easy to install but can't follow the sun so is 'peakier' than tracking PV.
   - Future grid-connected rooftop PV will need batteries and controlled inverters to prevent excess mid-day generation and voltage rise in distribution networks
5. **Concentrating solar thermal with molten salt storage**
   - Is cost effective for overnight generation.
   - Stores heat energy in molten salt tanks.
   - Does not generate in cloudy conditions (unlike PV)

Could the SWIS be powered primarily by solar PV and pumped hydro alone?

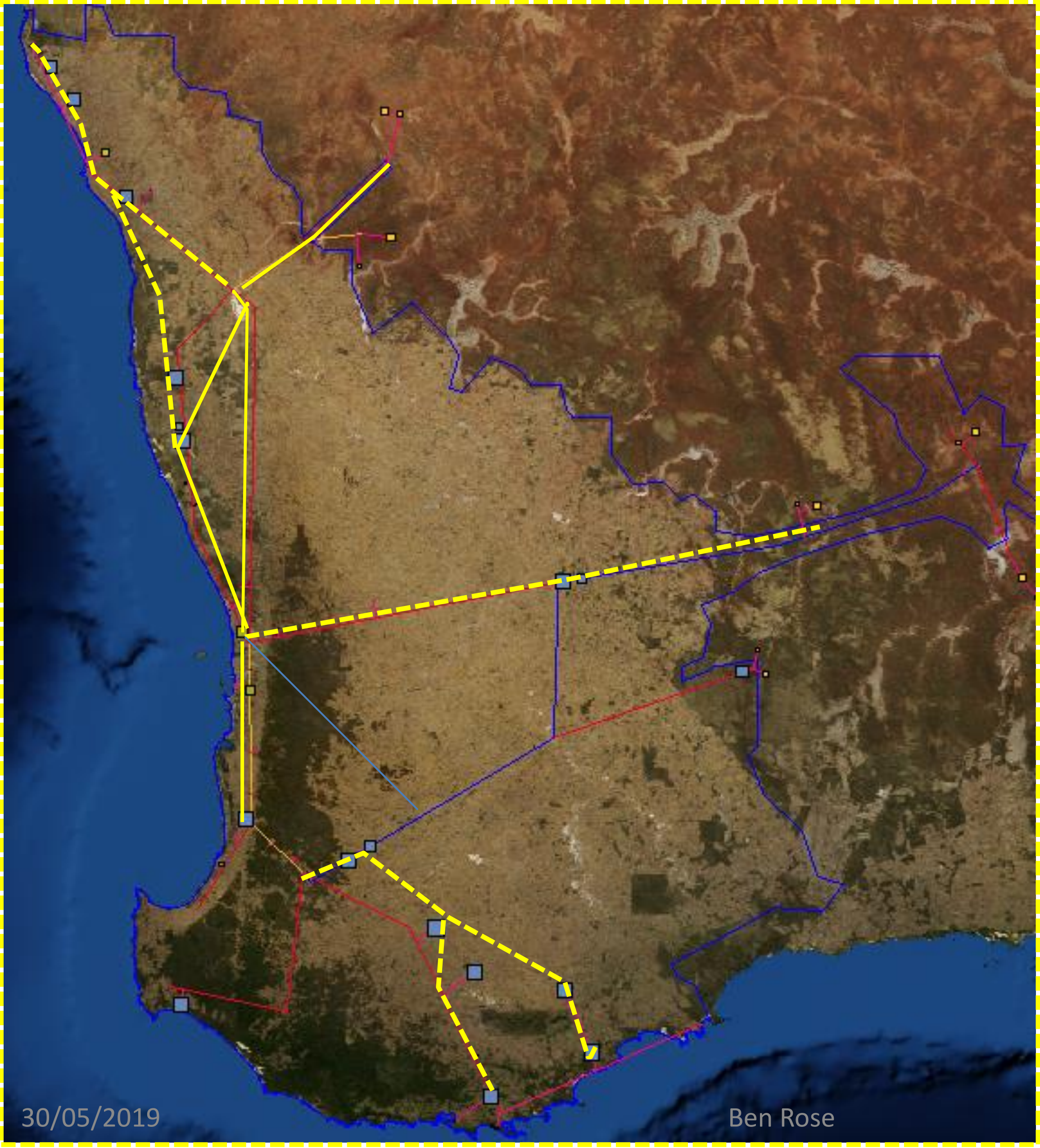
Yes, but at a higher cost than using combinations of wind and solar.

Modelled cost of 100% RE using single axis tracking PV and pumped hydro only:

- 2021-22 CAPEX of $1.429m/ kWh* for utility scale tracking PV gives LCOE of $164/MWh
- 2031-32 CAPEX of $0.954m/ kWh* gives LCOE of $138/MWh

* *AEMO, Aug 2018. Integrated System Plan Modelling Assumptions*

What about the cost of new transmission lines?



New HV transmission for RE will cost about $2.1 billion = 0.7c/ kWh for 30 years (has been included)

Cost of new 220 and 330 kilovolt transmission lines for 90% RE (9000 MW) = $2.1 billion. This equates to $7.20/ MWh or 0.7c/kWh

Name	Length to Metro (km)	Dispatchable?	Peak (MW) for station	Max. line MW = 5*MW/8	Line type	Cost per km	End stn cost $	Minus existing line (km)	Existing Line	Main line Distance to be costed (km)	Connector distance to be costed (km)	LINE COSTS
C Llewin stn	**362**		400.0	500	220 d	900,000	$8,000,000	218	330s (50%)	144	0	$137,600,000
Collie E			400.0				$8,000,000			0		$8,000,000
Collie E 2	240		400.0	500	330s	1,000,000	$8,000,000	218	330s	22	20	$50,000,000
Dongara stn			400.0		220d	900,000	$8,000,000			0	10	$17,000,000
Walkaway stn 2			400.0		220d	900,000	$8,000,000			0	10	$17,000,000
Walkaway stn			400.0		220d	900,000	$8,000,000			0	10	$17,000,000
Oaka stn	385		400.0	1,000	330d	1,500,000	$10,000,000	275		110		$175,000,000
Horrock Station 2			400.0		220d	900,000	$8,000,000			0	10	$17,000,000
Northampton Station	445		400.0	500	330s	1,000,000	$8,000,000	400	220d	45		$48,500,000
Harvey			400.0		220d	900,000	$8,000,000			0	10	$18,000,000
Waroona	127		400.0	500	330s	1,000,000	$8,000,000	218	330s	0	10	$18,000,000
Lancelin stn		y	400.0		220d	900,000	$8,000,000			0	20	$26,000,000
Jurien stn 2	250		400.0	500	220d	900,000	$8,000,000			250	50	$278,000,000
Kojonup 1&2, Mt Barker)	301		800.0	500	330d	1,500,000	$10,000,000	218	330d	83	20	$164,500,000
Kronkup stn			400.0		220d	900,000	$8,000,000			0	47	$50,300,000
Mt Barker stn	420		400.0	500	330s	1,500,000	$10,000,000				10	$25,000,000
Merredin stns 1& 2	243		800.0	500	220d	900,000	$8,000,000			243	20	$244,700,000
Wellstead stn		y	400.0		220d	900,000	$8,000,000			0	10	$17,000,000
Wellstead stn 2	487		400.0	1,000	330d	1,500,000	$10,000,000	218	330d	269		$413,500,000
220 km 330 double line for CST				1,000	330 D	1,500,000	$10,000,000	219	330d	220		$340,000,000
	Up to 10,000 MW of dispersed utility-scale wind and solar							**New line km W, PV**		**1386**	**257**	
							10,000,000				**New transmission cost**	**$2,082,100,000**
											Value of existing transmission	**$1,791,000,000**

Annualized cost of new transmission for 5300 MW of dispersed wind, PV and CST replacing all coal, is < $3/MWh, i.e. 0.3c /KWh (with WACC 6% /30yrs)

Scenario: RE Equiv. C to CCS Retrofit **Name of power station or transmission line**	**Power station peak power (MW)**	**Maximum capacity (MW) of main transmission line***	**Line type (kV, single (s) or double (d)**	**Cost per km**	**Cost of End Stations**	**Main line distance to be costed (km)**	**Connector distance to be costed (km)**	**LINE + END STATION COSTS**
Kojonup Wind	400		330s	$1,000,000	$8,000,000	n/a	0	$8,000,000
Collie E Wind	400		330s	$1,000,000	$8,000,000	n/a	20	$28,000,000
Kojonup to Collie line		500	330s	$1,000,000	$8,000,000	111	n/a	$119,000,000
Harvey Wind	500		330s	$1,000,000	$8,000,000	n/a	10	$18,000,000
Collie to Perth line		1000	330d	$0	$0	0 (existing line)	n/a	0
Karara PV	250		330s	$1,000,000	$8,000,000	n/a	10	$18,000,000
Eneabba Wind	400		330s	$1,000,000	$8,000,000	n/a	20	$28,000,000
Cervantes Wind	400		330s	$1,000,000	$8,000,000	n/a	40	$48,000,000
Three Springs to Perth line		1000	330d	$1,500,000	$0	275	n/a	$412,500,000
Merredin Wind	500		330s	$1,000,000	$8,000,000	n/a	20	$28,000,000
Southern Cross PV	250		330s	$1,000,000	$8,000,000	n/a	0	$8,000,000
Southern Cross to Perth line		500	330s	$1,000,000	$8,000,000	228	n/a	$236,000,000
Metro PV	1200	n/a	n/a	n/a	n/a	0	n/a	0
MW of utility scale wind and PV using new transmission lines				**3,100**	**Total cost of new lines plus sub-stations**			**$951,500,000**
MW of Rooftop PV not requring new transmission lines				**1200**	**Total transmission line kilometres**			**734**
						Annualized cost per MWh		**$ 2.93**

* A '5/8' rule is applied: Transmission line capacity need only be 5/8th of the maximum capacity of all generation feeding into it. This is because it is assumed that power exceeding 5/8th of maximum will be curtailed (this amounts to less than 4% of total energy generated). For example, wind or solar power stations totalling 800 MW capacity can feed into a transmission line with only 500 MW of capacity.

Note: 1000 MW of PV in metro area not included as no transmission needed

10 take-away points

1. **80-85% renewables – Electricity cost likely to be not significantly different to** current SWIS electricity, and CO_2 would be reduced by >80%.

2. **All new 'HELE' coal and gas would cost at least as much as 85% RE** and reduce CO_2 by < 20%

3. **Coal and gas steam thermal doesn't mix with increasing RE** – cost increases and reliability declines due to increased ramping and stop-starts.

4. **State needs to own / control entire fleet (2600 MW) of fast ramping OCGT's.**
   - Start upgrading now to a fleet of modern aero-derivative dual fuel units.
   - Ensure adequate peak gas supplies for the RE transition period.

5. **Phase out coal and gas steam thermal quickly** as RE increases, until all closed at 65% RE. Close each ST generator unit as soon as sufficient RE is commissioned to replace it.

6. **50% RE by 2030 needs to be a MINIMUM target –** utilities will want to get rid of all coal and gas ST due to increasing costs and outages.

7. **Accelerate installation of wind and utility PV.**
    - Govt. can order WP to **install new HV transmission lines** to south, north and east to connect new RE at the best locations.

8. **New properly resourced Govt. RE agency** to plan roll-out and manage future PPA's (power purchase agreements) for renewable energy.

9. **Plan, procure sites and install large scale storage.** Grid scale batteries (immediately), CST Molten Salt and Pumped Hydro Storage - up to 6 year lead time.

10. **No need to wait until new regulations such as constrained access or a new RE agency are enacted**. Govt. owns 72% of coal, >50% of gas steam thermal. Can control closure of these. Owns the Western Power grid– can order WP to install new transmission to connect new RE. Owns Synergy – can order them to let tenders for preliminary Power Purchase Agreements for more RE quickly.

SWIS transition to RE – jobs revolution

- 1400 new permanent jobs (700 more than currently in coal)
- 8,500 construction and manufacturing jobs for 5 years

Supplementary slides

Wind and PV generation is predictable in advance

- Forecasting wind and solar is increasingly accurate. The Australian Wind Energy Forecasting System (AWEFS) provides accurate forecasts of wind generation
- Down to 5 minutes in advance, for individual wind farms and regions.
- Proven in practice world-wide to allow adequate time for dispatch of stored or fuelled energy to compensate for falling RE generation.

Formula for calculating Levelised Cost of Energy (LCOE)

$$C_{Ed} = (P \times C_{fa}) + (E_g \times C_v)$$

$C_{Ed} = Cost\ of\ electricity\ generated$

$P = Rated\ power\ capacity$

$C_{fa} = Fixed\ annual\ cost\ per\ unit\ of\ capacity$

$E_g = Electricity\ generated$

$C_v = Variable\ costs$

ELECTRIC VEHICLES

- **GRID DEMAND** - 20% EV's should only increase grid demand by 6%
- 100% EV's should increase grid demand by <40%
- Potential to reduce transport carbon emissions by >70% once electricity is clean.
- European countries already planning for phase out of petrol and diesel vehicles.
- Heavy 'stop-start' vehicles best candidate for electrification
- Government needs to plan and fund implementation of:

❑ Networks of fast charging points for day-time charging*

❑ Electrification of Transperth buses

❑ Electrification of municipal rubbish compactors and trucks

**EV charging from parking lots will utilise cheap excess PV best during middle of the day*

Description	Quantity in 2017 (all types)	Estimated % of EVs	Total EVs	Average Daily Distance Driven (km)	Energy Required (kWh/ km)	Total Energy (MWh/ day)	Notes
Personal Vehicles	1,645,748	20%	329,150	30	0.1	987	ABS reports 2,142,307 registered vehicles in WA in 2014. Assume 75% are passenger vehicles (general ratio for Aus.) and 90% of these are in the SWIS. Also 1% increase per year till 2030.
Light Commercial Vehicles	292,578	20%	58,516	80	0.3	1,404	ABS reports 2,142,307 registered vehicles in WA in 2014. Assume 24% are light commercial vehicles (25% general ratio for light and heavy commercial vehicles for Aus.) and 50% of these are in the SWIS. Also 1% increase per year till 2030.
Heavy Commercial Vehicles	12,191	20%	2,438	400	1	975	Assume 1% of WA vehicles are heavy commercial vehicles (25% general ratio for light and heavy commercial vehicles for Aus.) and 50% of these are in the SWIS. Also 1% increase per year till 2030.
				Total		**3,367**	

Have assumed a modest growth rate in vehicles of 1% pa.

Have assumed that EV efficiency improves slightly to 0.1 kWh/km. Not expected to improve significantly as mostly due to car aerodynamics which have already progressed along the learning curve significantly.

Average daily km for commercial vehicles is based on a mixture of light utilities and cars at low energy per km mixed with larger trucks at up to 1kWhr per km

Heavy vehicle energy usage based on typical figures from Wikipedia "https://en.wikipedia.org/wiki/Electric_truck" and derated to allow for learning curve

Plexos – energy software used by Synergy, AEMO
NEMO – Powerful computer-optimized software invented by UNSW
Used in studies by:
Blakers at al, ANU
Elliston et al, UNSW

Similar conclusions for NEM as this SIREN-Powerbalance modelling of SWIS:

- *100% renewable electricity is attainable*
- *Storage is essential – mainly PHS*
- *Small amount of fueled backup occasional use – about 5% of generation*

SIREN electricity modelling of Solar Thermal, fixed PV, tracking PV at Southern Cross, 2017

Power Station Name	Technology	Capacity (MW)	Capacity Factor	Generation MWh)
Southern Cross CST	Solar Thermal	500.00	0.28	1,220,336
Southern Cross rtPV	Fixed PV	500.00	0.23	1,029,186
Southern Cross tracking PV	Tracking PV	500.00	0.30	1,319,636

How to make a just transition for Collie ?

Short term 5 year

- **Viable future options for coal workers**
  - Retraining in wind industries, mine rehabilitation, tourism.
  - Voluntary redundancy packages
- **Wind Installation hub**
  - Construction base at Collie for > 1000 MW of wind.
- **Fabrication industries at Kemerton, Collie or Bunbury:**
  - Wind turbine towers and blades, solar panel mountings.

Potential in the longer term

- **Biomass industries at Collie ($30m pledged by Labor):**
- **Power generation at Collie (best with CST storage)**
- **Biomass pellet export industry**
- **Pyrolysis bio-oil production: fuel for OCGT's & aviation**
- **New rail Collie to Wagin / Katanning** transporting biomass and other agricultural commodities to Collie and Bunbury port

Cost/MWh of refurbishing Muja CD to run another 8 years, assuming cost of $0.5b amortized over 8 years

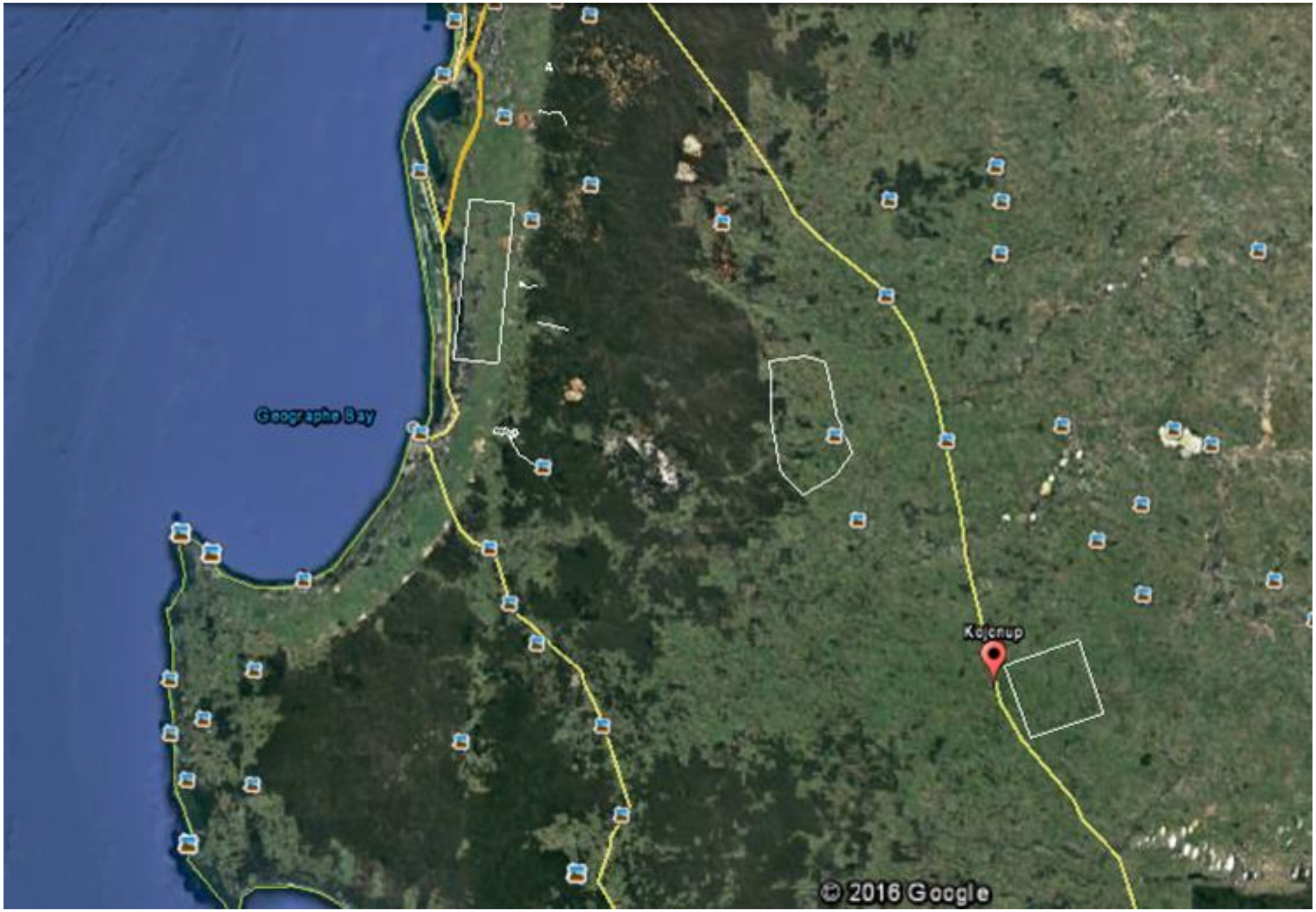
	Muja CD cost/MWh	
Upgrade Costs	$500,000,000	$320< spent on Muja AB, so this would be for Muja CD and Collie
Life extension (yrs.)	8	Unlikely to extend by this much but to be optimistic
Cost per year (4% interest)	$86,526,154	
Power Capacity (MW)	808	For Muja CD
Capacity factor	80%	Bit optimistic but gives a conservative answer
Energy per year (MWh)	5,662,464	

New wind and solar jobs in WA replacing Muja ABCD and Collie power stations

Technology	C & I (job yrs)	O & M (job yrs)	Manuf. (job yrs)	Capacity (MW)	C & I	Manufact-uring	O & M
Roof-top PV	13	0.7	6.7	890	11,570	5,963	623
Utility scale Solar PV	13	0.7	6.7	490	6370	3,283	343
Wind Farm	3.2	0.3	4.7	1,820	5,824	8,554	546
Biomass Facility	14	1.5	2.9	400	5,600	1,160	600
Transmission (734 km, $0.95 billion) **					7,300		
Minus permanent jobs lost from closing coal*	n/a	0.14	n/a	-1,300	n/a	n/a	-672
TOTALS (JOB YEARS)					**36,664**	**17,800**	
TOTAL (NET JOBS in WA)					**7,333**	**1,200***	**1,441**
****Assuming 20% of manufacturing jobs are in WA***					(for 5 years)	(for 5 years)	(perm-anent)

POTENTIAL NEW JOBS FOR COLLIE AND SW REGION

Technology	C & I (job yrs)	O & M (job yrs)	Manuf. (job yrs)	Cap. (MW)	Construct & Install	Manuf-acturing	O & M	When
Utility scale Solar PV	13	0.7	6.7	200	2600	1,340	140	2017-2021
Wind Farm	3.2	0.3	4.7	1,000	3,200	4,700	300	2017-2021
Biomass Facility	14	2	3	400	5,600	1,160	600	2021-2030
Transmission (140 km) **					1,400			2017-2021
Mine pit rehabilitation							50	2017-2030 ?
Minus permanent jobs lost from closing coal*	n/a	0	n/a	-1,300	n/a	n/a	-672	
TOTALS (JOB YEARS)					12,800	6,040		
TOTAL Net full time jobs (> 5 year) in WA by 2030					**2,560**	**400***	**419**	
** Assume 33% of manufacturing will be in Collie- Bunbury region*					**for 5 yrs**	**for 5 yrs**	**Permanent**	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