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Pumped hydro storage and 100% renewable electricity

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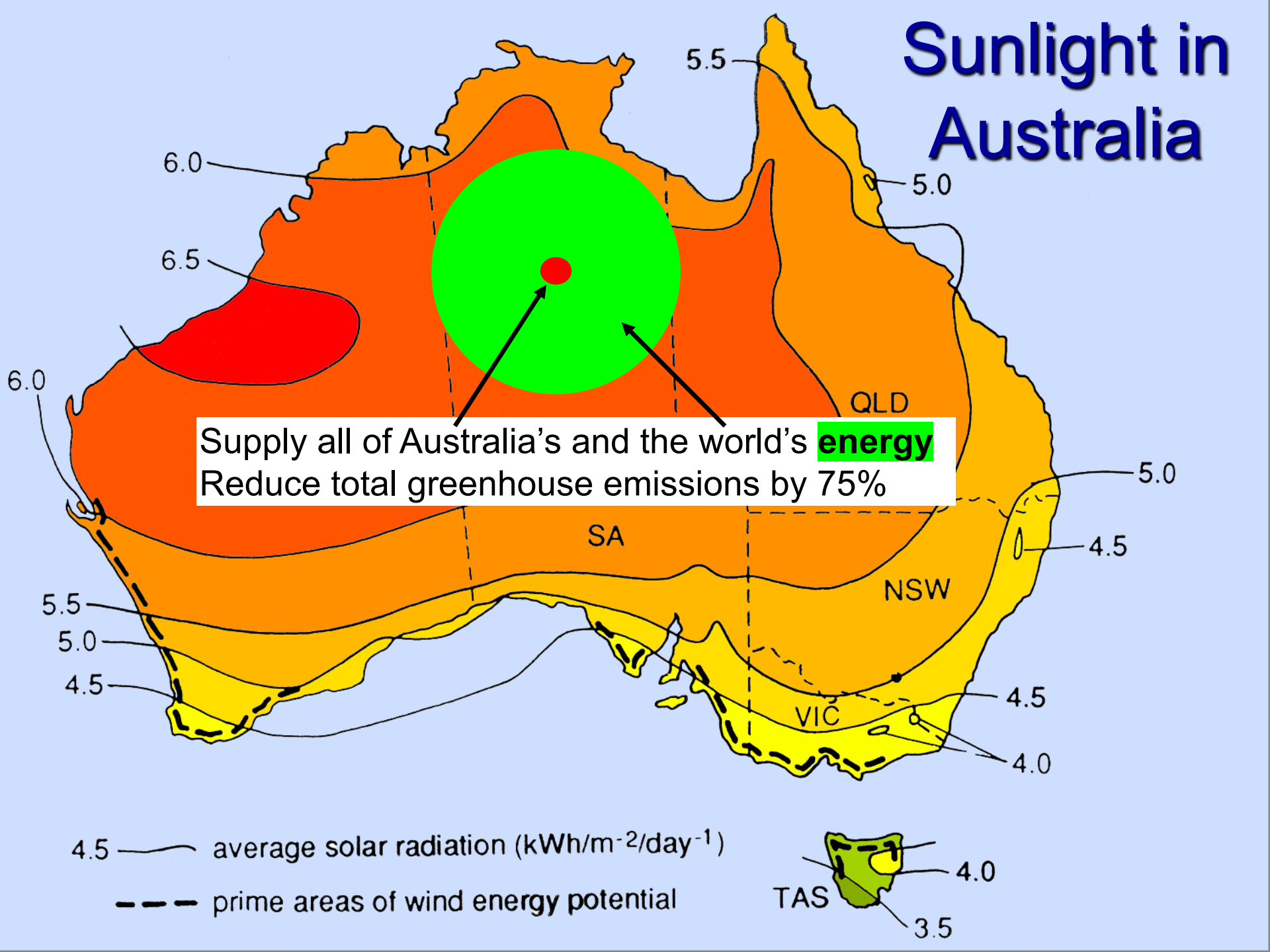
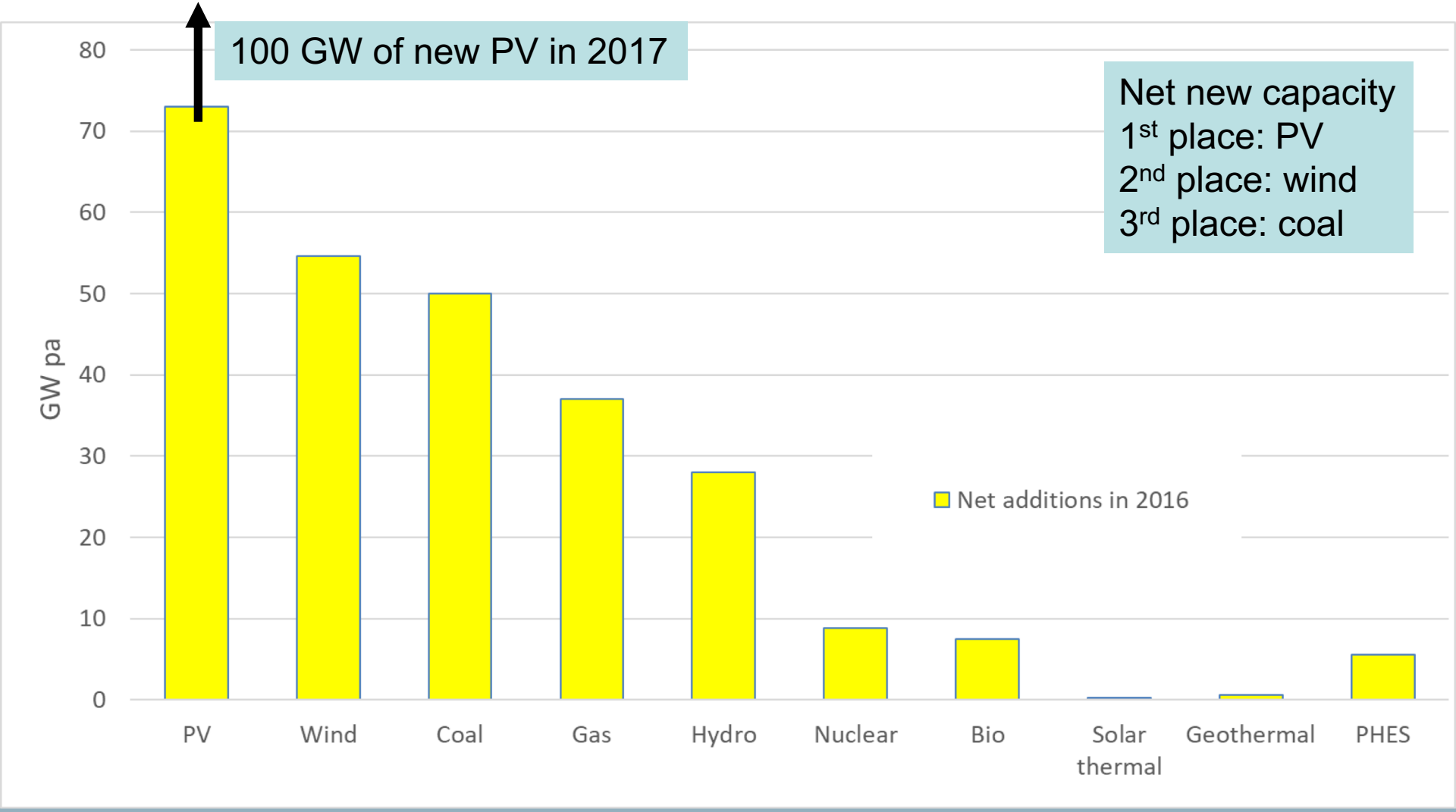
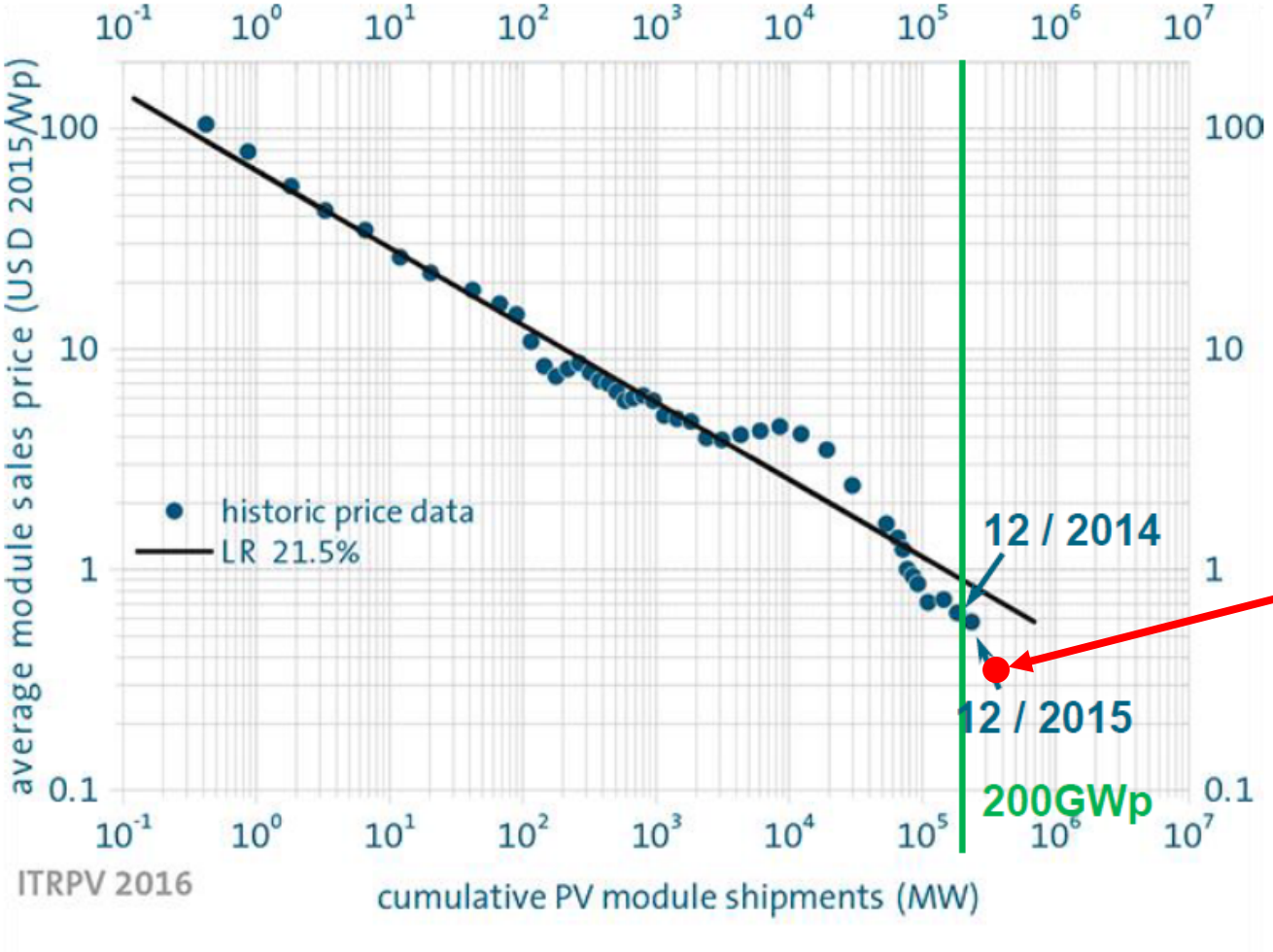
Sunlight in Australia



New generation capacity worldwide in 2016



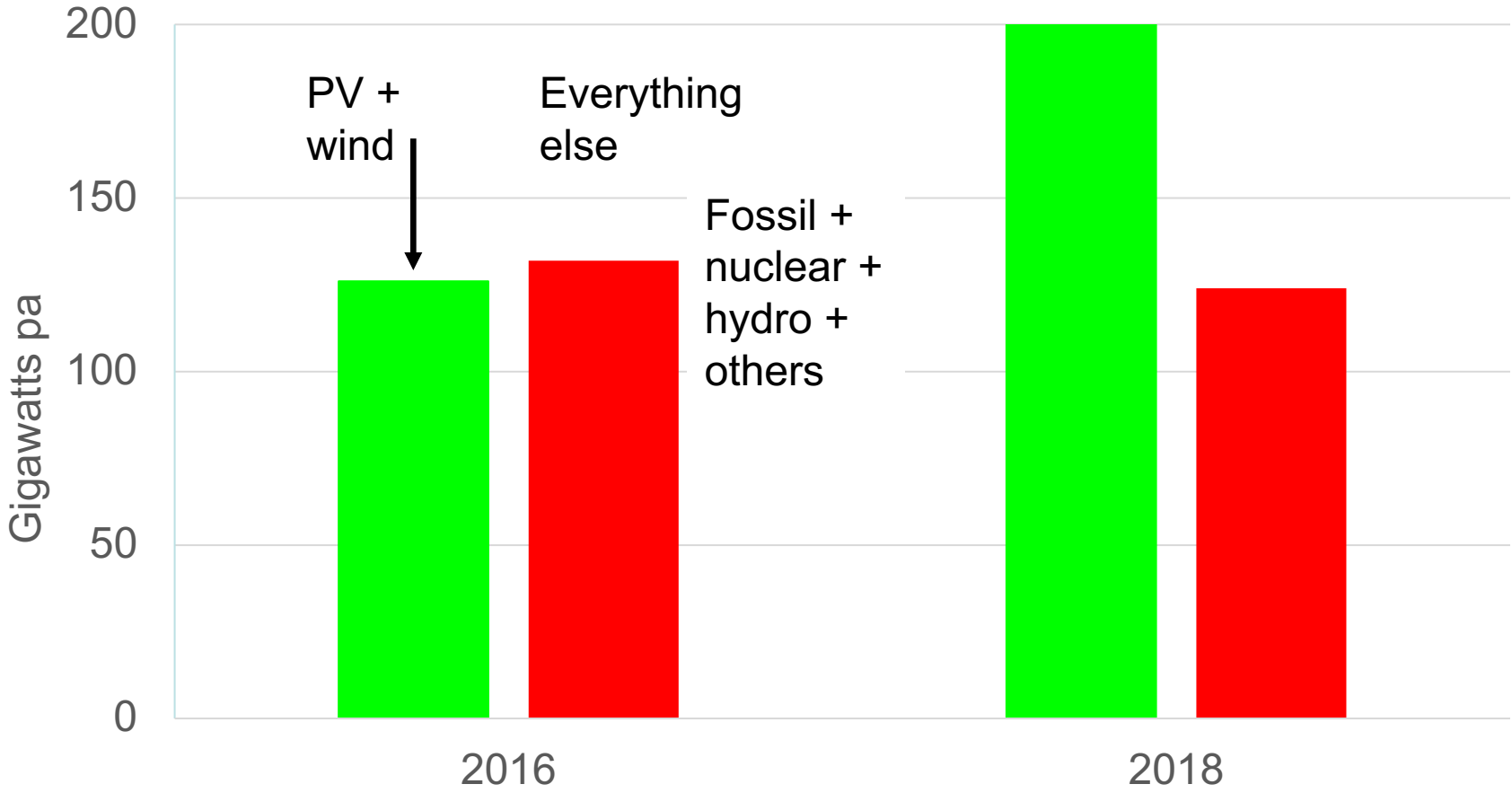
PV learning curve



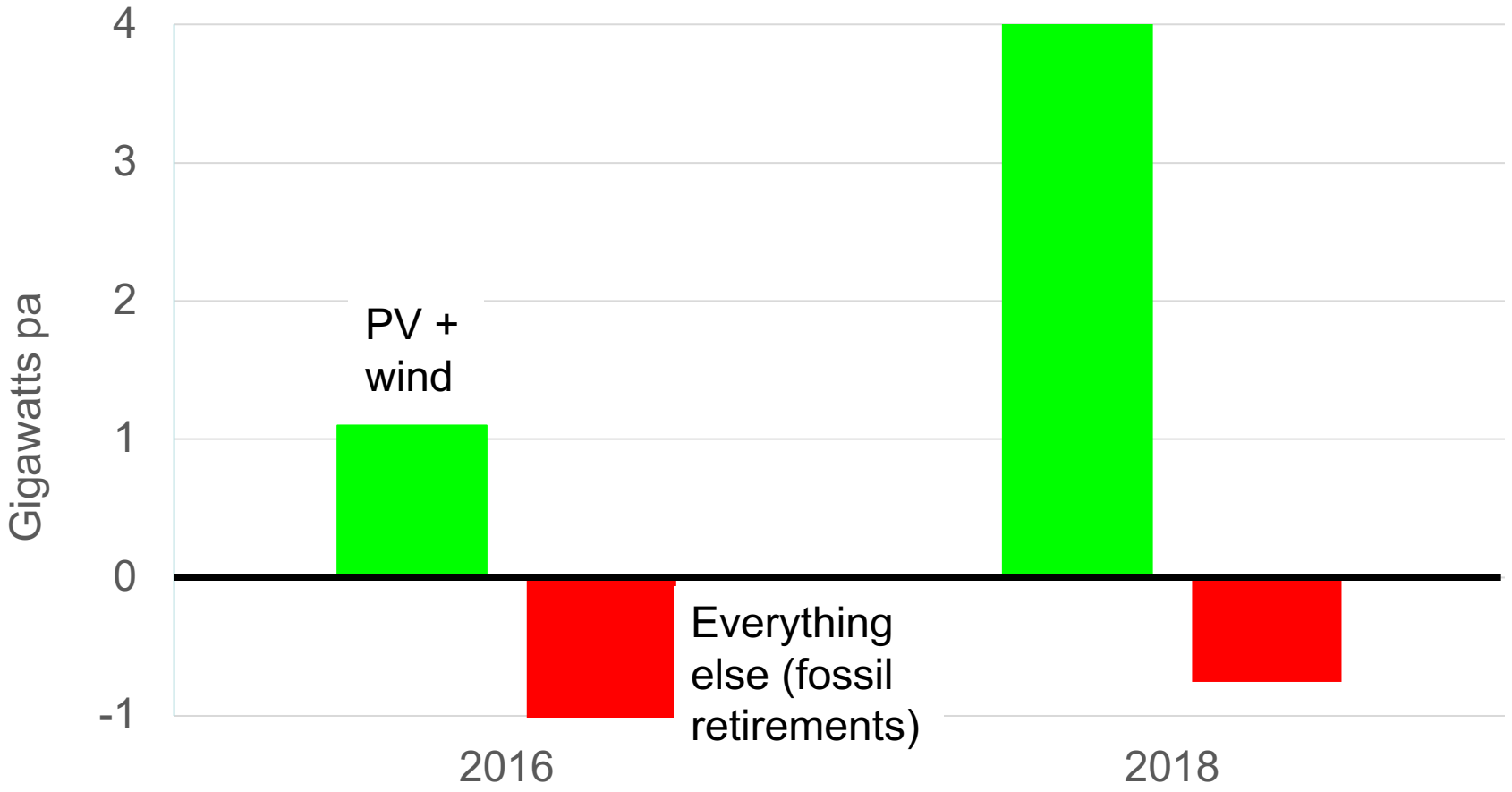
Late 2017

380 GW

Net new generation capacity (GW) Estimate for 2016 & 2018 - worldwide

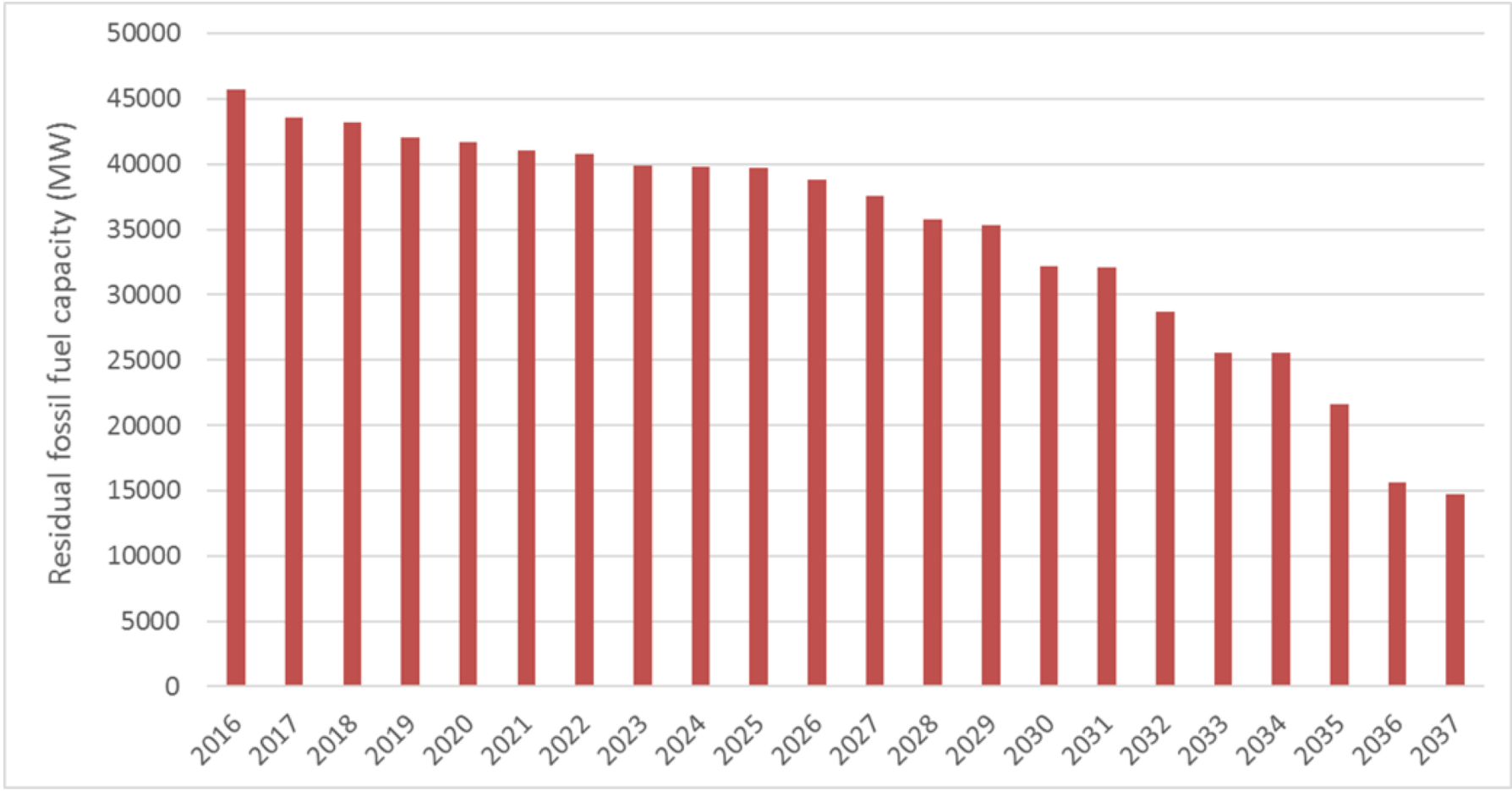


Net new generation capacity (GW) Estimate for 2016 & 2018 - Australia



Retirement of existing fossil fuel plant

- PV and wind are replacing retiring plant



Renewable electricity shares

- Tasmania: 100% now
- ACT: 100% by 2020
- South Australia: 75% by 2025
- Victoria: 40% by 2025
- Qld: 50% by 2030
- NT: 50% by 2030
- WA, NSW, Federal: no targets

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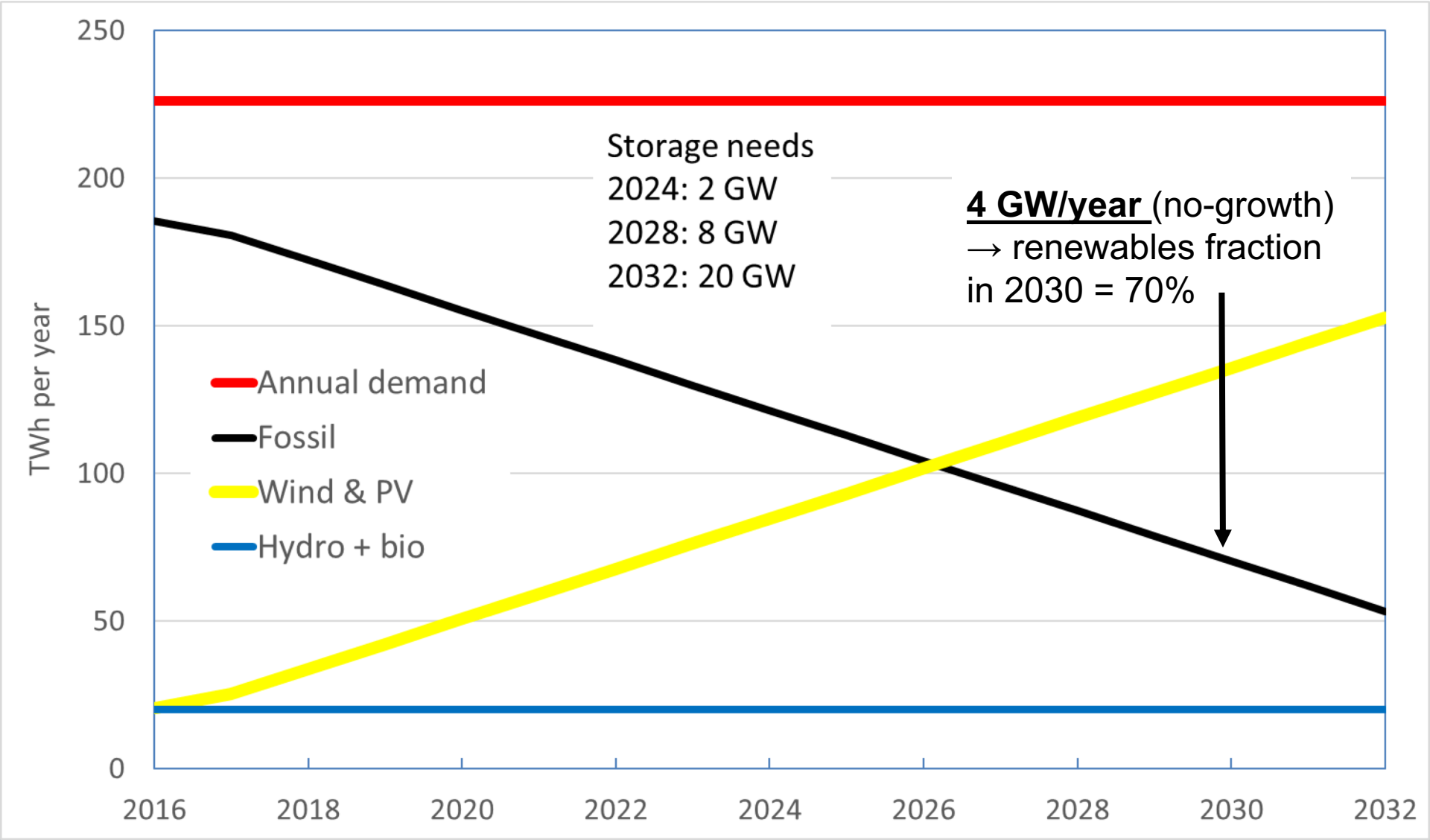
Australian electricity supply & demand



100% renewable electricity is coming fast

often blows at night

- Technical diversity
  - 90% PV and wind (+ existing hydro & biomass)
- Wide geographical dispersion hugely reduces required storage
  - High voltage interconnectors
- Demand management
  - Shift loads from night to day, interruptible loads
- Mass storage
  - Pumped hydro: 97% of all storage
  - Advanced batteries

High voltage DC transmission (HVDC)

Storage & HVDC belong together

HVDC: Transmit Gigawatts at Megavolts over thousands of km

- Basslink: 400kV, 290km, 0.5GW
- ABB (China): **1100kV, 3000km, 12GW**

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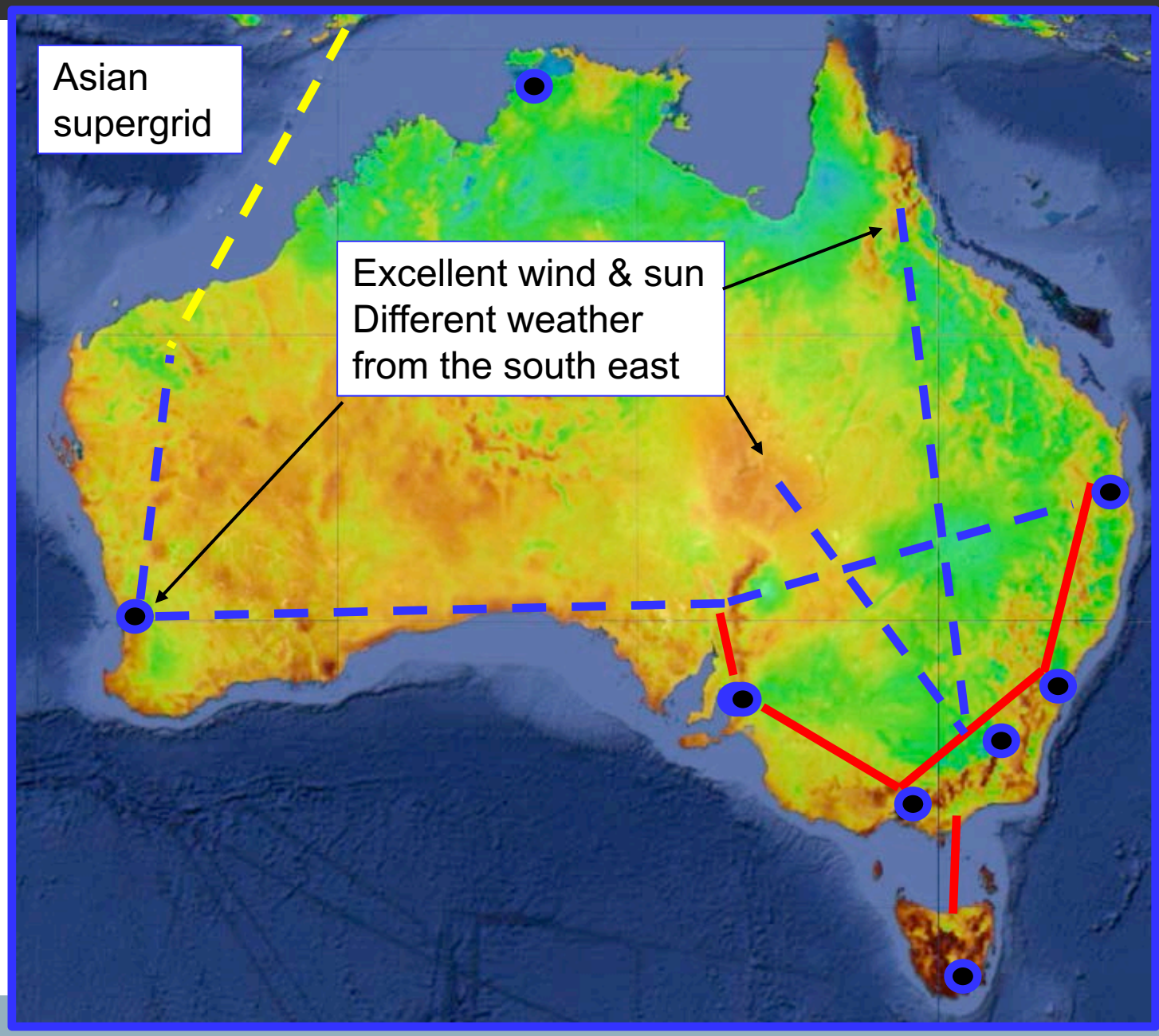
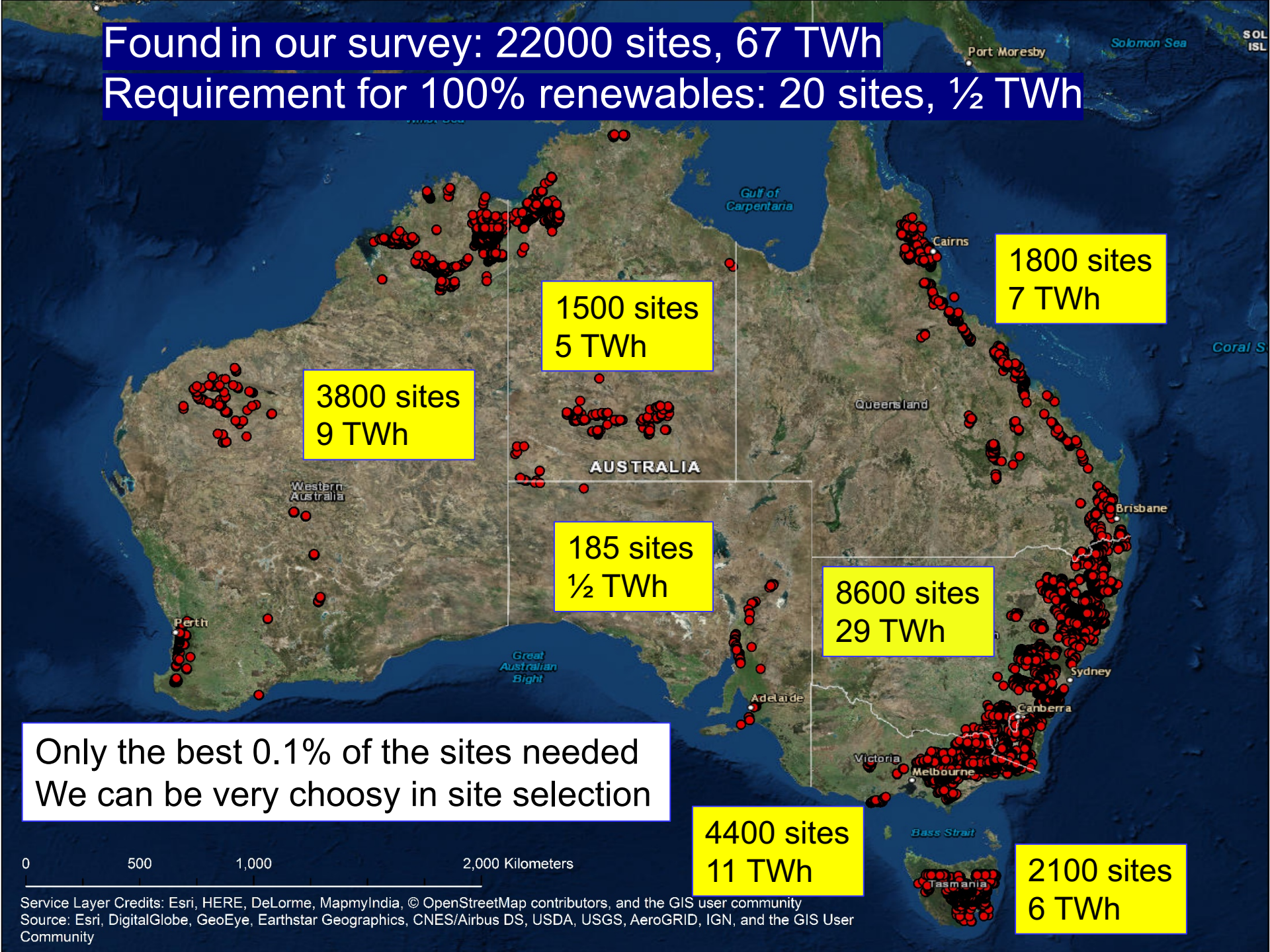
HVDC/AC backbones



Automated GIS pumped hydro site search

- Minimum head: 300m (200m in WA, NT)
- Minimum stored energy: 1 GWh
- Minimum pipe/tunnel slope: 1:15
- Exclude national parks and urban areas
- 99% of sites are off-river (closed loop)
- Research program
  - Find upper reservoirs
  - Find lower reservoirs and pair them
  - Develop public cost model (GHD, B&V, ANU)


Found in our survey: 22000 sites, 67 TWh
Requirement for 100% renewables: 20 sites, ½ TWh
Port Moresby
Solomon Sea
Gulf of Carpentaria
Cairns
1800 sites
7 TWh
1500 sites
5 TWh
3800 sites
9 TWh
Queensland
AUSTRALIA
Western Australia
Brisbane
185 sites
½ TWh
8600 sites
29 TWh
Perth
Great Australian Bight
Sydney
Adelaide
Canberra
Victoria
Melbourne
Only the best 0.1% of the sites needed
We can be very choosy in site selection
4400 sites
11 TWh
Bass Strait
Tasmania
2100 sites
6 TWh
0
500
1,000
2,000 Kilometers
Service Layer Credits: Esri, HERE, DeLorme, MapmyIndia, © OpenStreetMap contributors, and the GIS user community
Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

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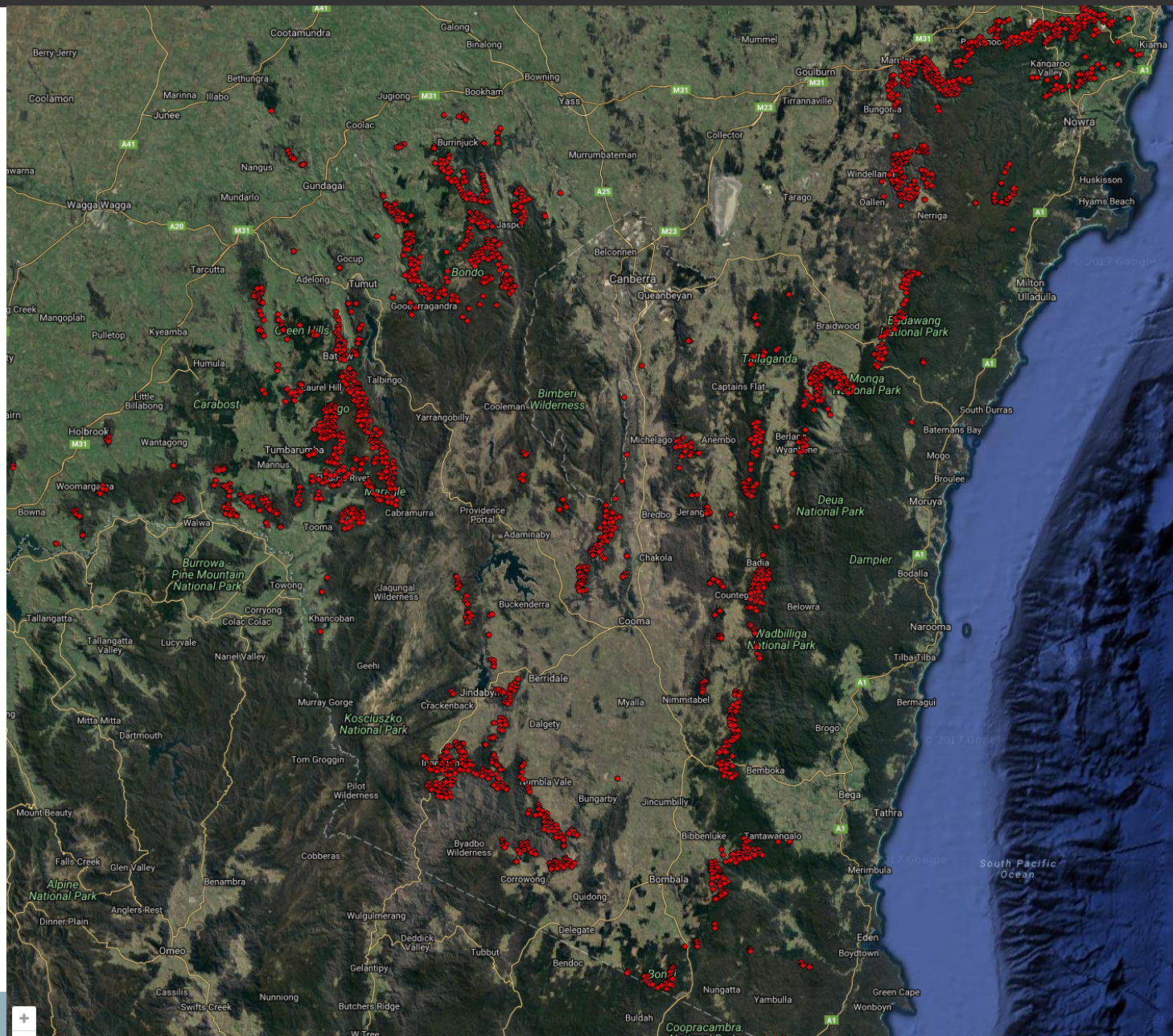
SE-NSW



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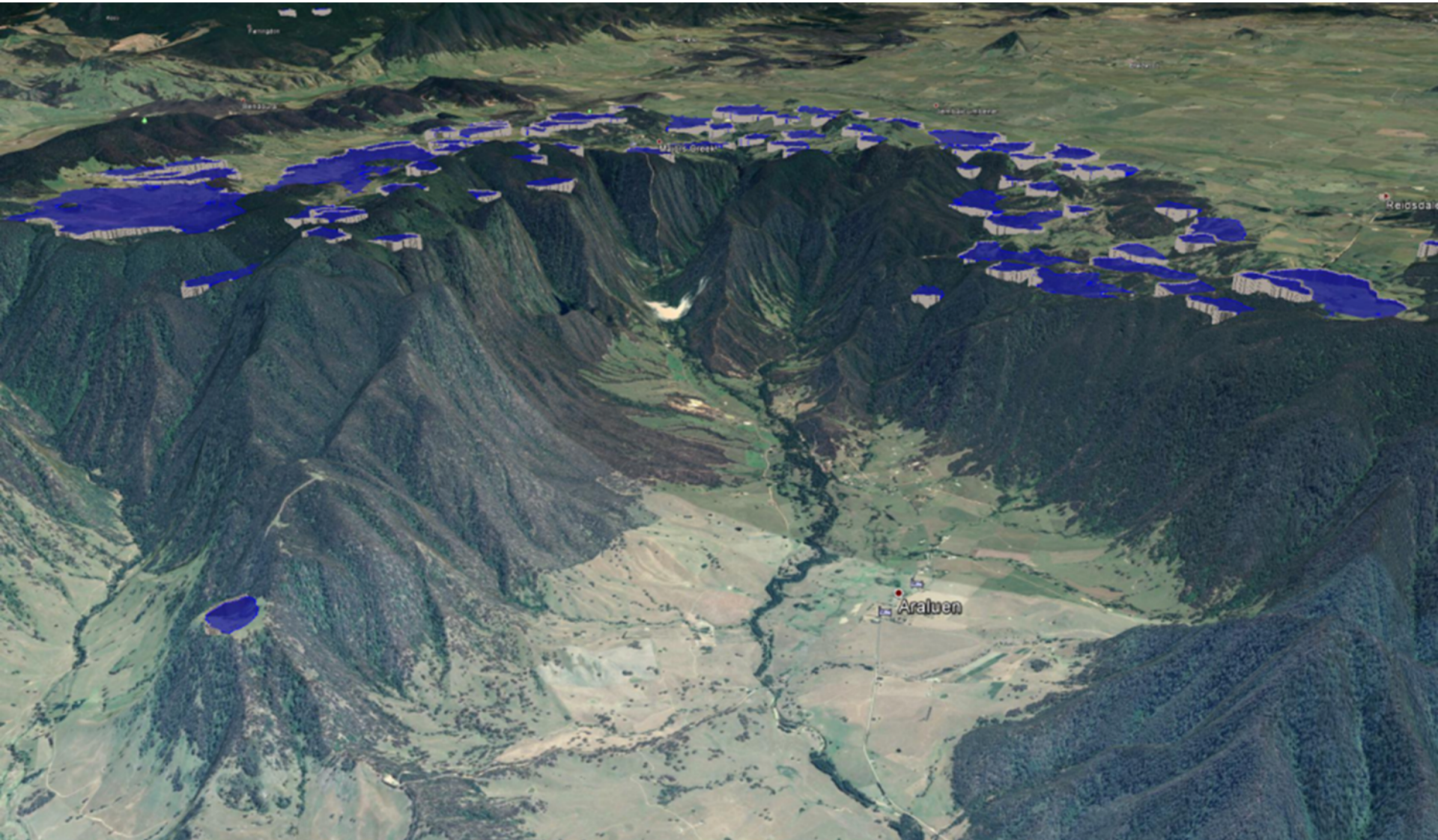
Araluen (near Canberra)



Brown Mtn, NSW

Next steps in STORES

Feature	Initial survey (2017)	Refined survey (2018-19)
Find upper reservoirs	Yes (22,000)	Yes
Lower reservoirs	-	Yes
Pairing of upper & lower	-	Yes
Minimum head (metres)	300	150
Dam wall height (metres)	40 (fixed)	10-80 (variable)
Minimum slope	1:15	1:15
Optimise penstock route	-	Yes
Integrate cost model	-	Yes
Ranking	-	Yes
Automated searching	-	Yes

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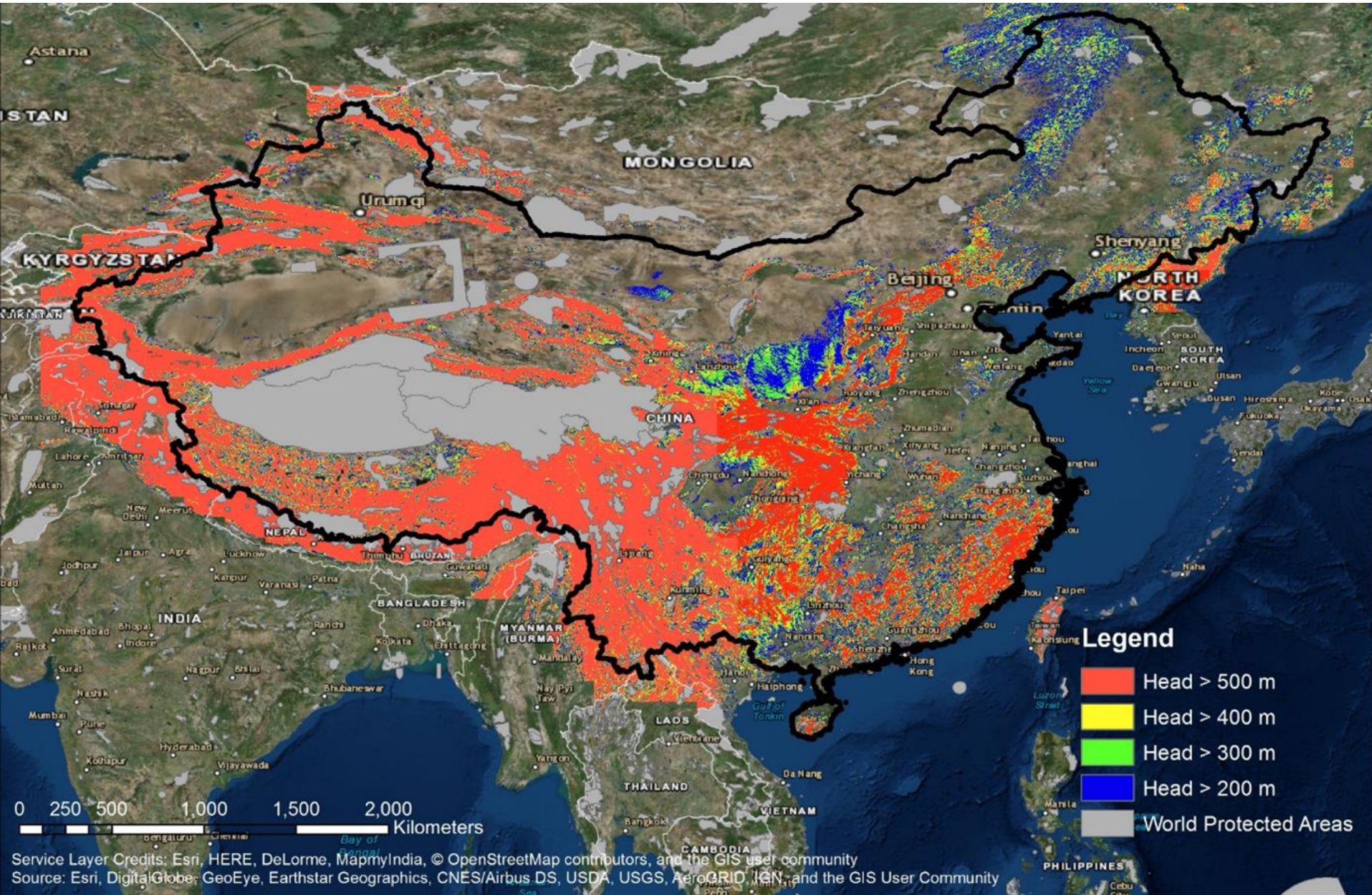
China



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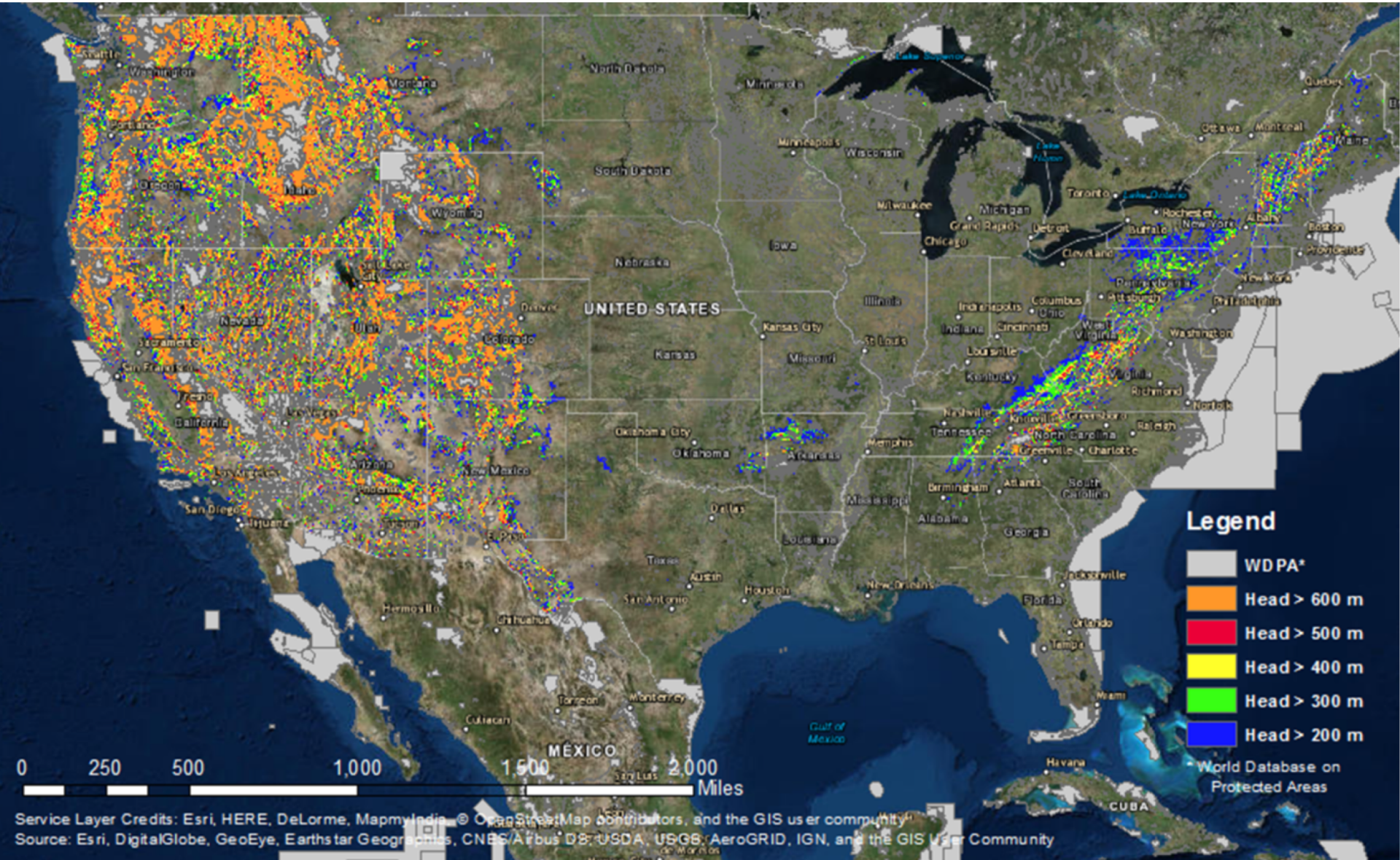
USA



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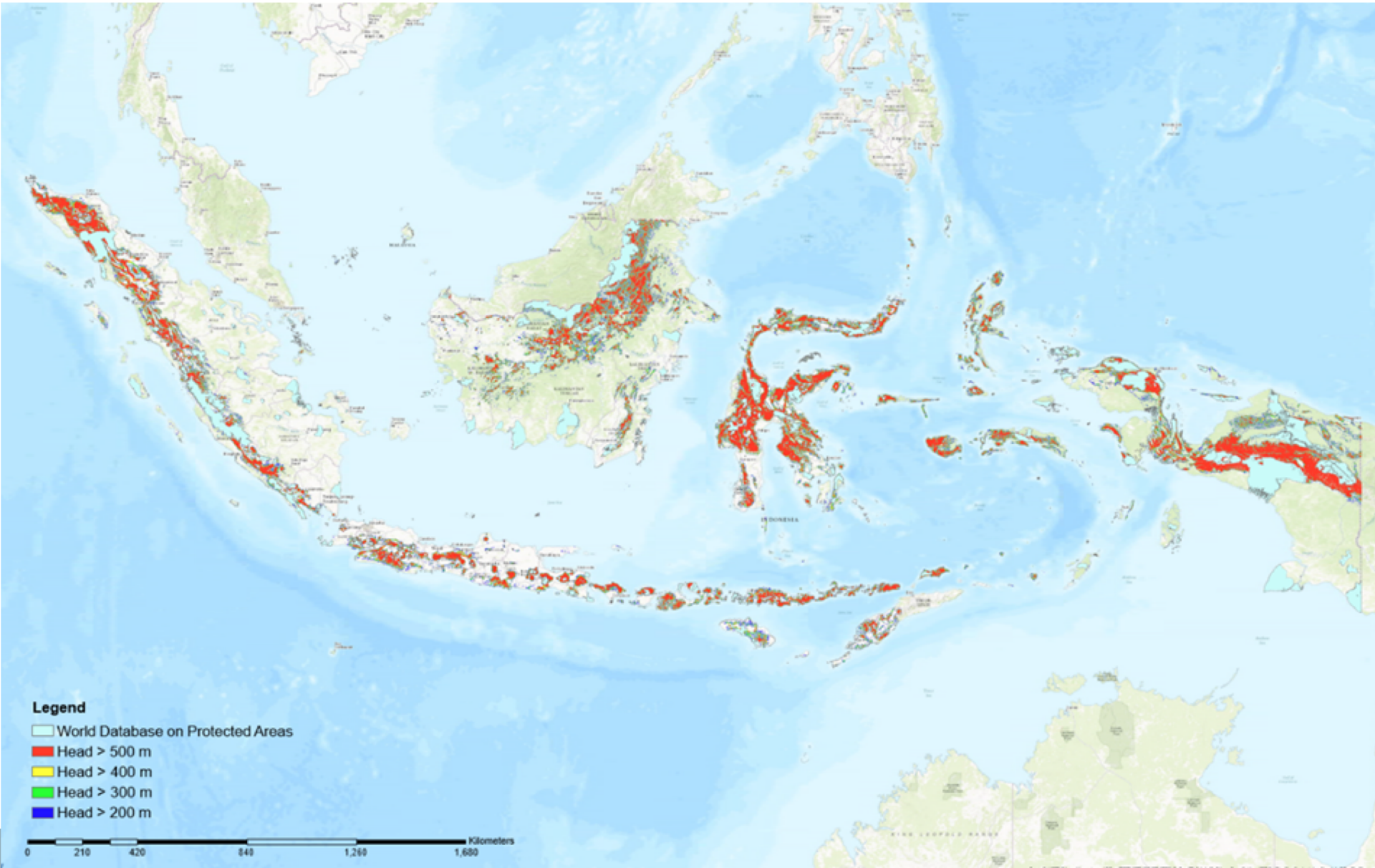
Indonesia



PHES: water and environment - 100% renewables scenario

- Environment
  - Exclude national parks
  - Australia: 36 km^2 total reservoirs (5 ppm)
- Water
  - Water recycled; evaporation suppressors
  - PV/wind/PHES system uses ¼ of the water used by a coal-dominated system

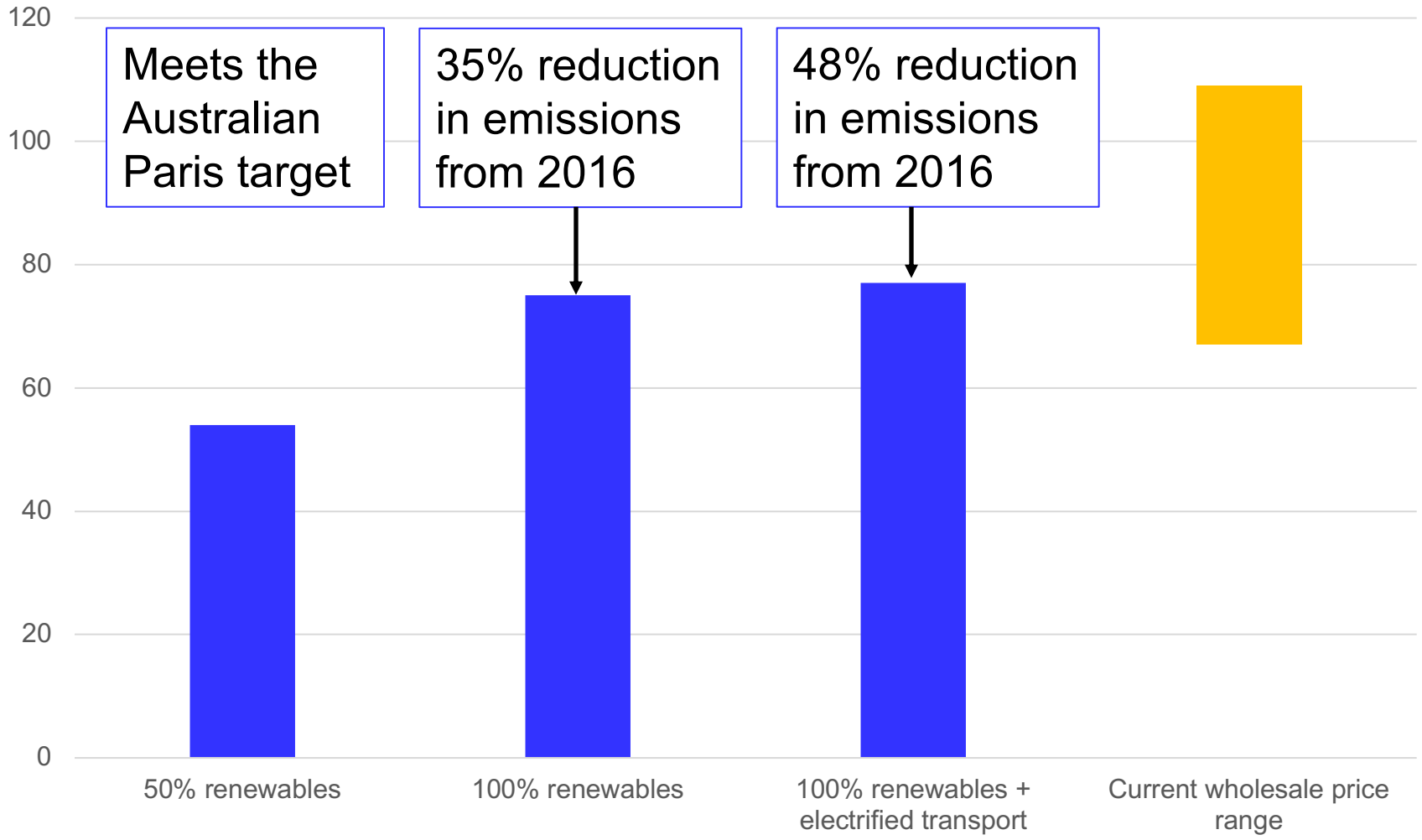
Modelling 100% renewable electricity

- No heroic assumptions: only use technologies in mass production
  - PV, wind, pumped hydro, HVDC/AC
- Hourly demand, wind, sun data for 2006-10
- 90% PV + wind
  - 10% existing hydro and biomass
- Very widely distributed over 1 million km^2
  - Wide range of weather, climate, demand
- Pumped hydro energy storage (PHES)
  - Plus batteries and demand management

Balancing 100% renewables

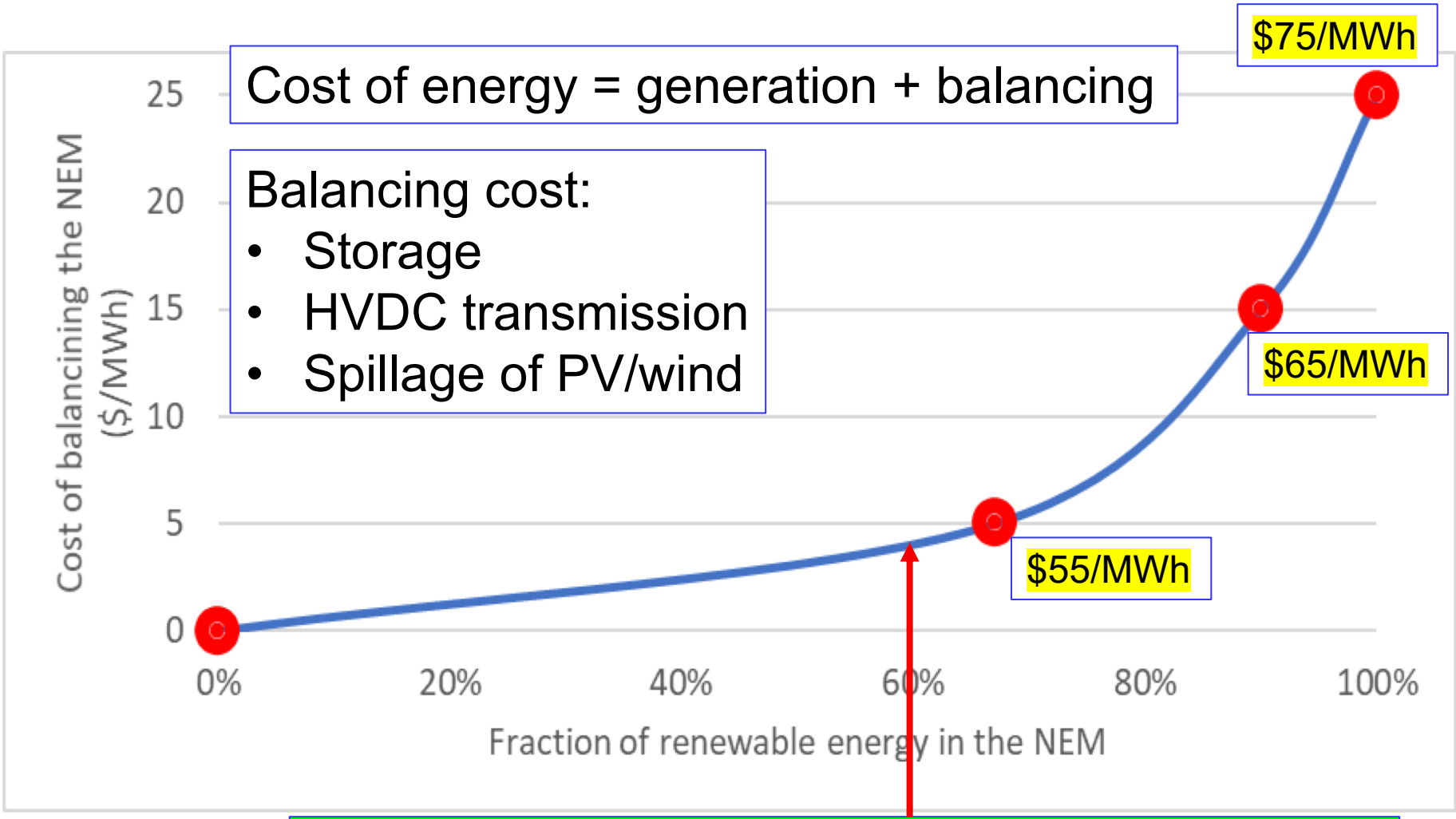
- Balancing cost = storage + HVDC + spillage
- For 100% renewables: $25 per MWh
  - Storage = $12
  - HVDC = $7
  - Spillage of PV/wind = $6
- Storage requirements
  - 450 GWh of energy storage
  - 20 GW of storage power capacity
  - Spread across about 20 sites

All-in cost of electricity



Cost of hourly balancing

Balancing 100% = 20 GW + 450 GWh



Balancing 60% = Snowy 2.0 + 2GW for 6 hours

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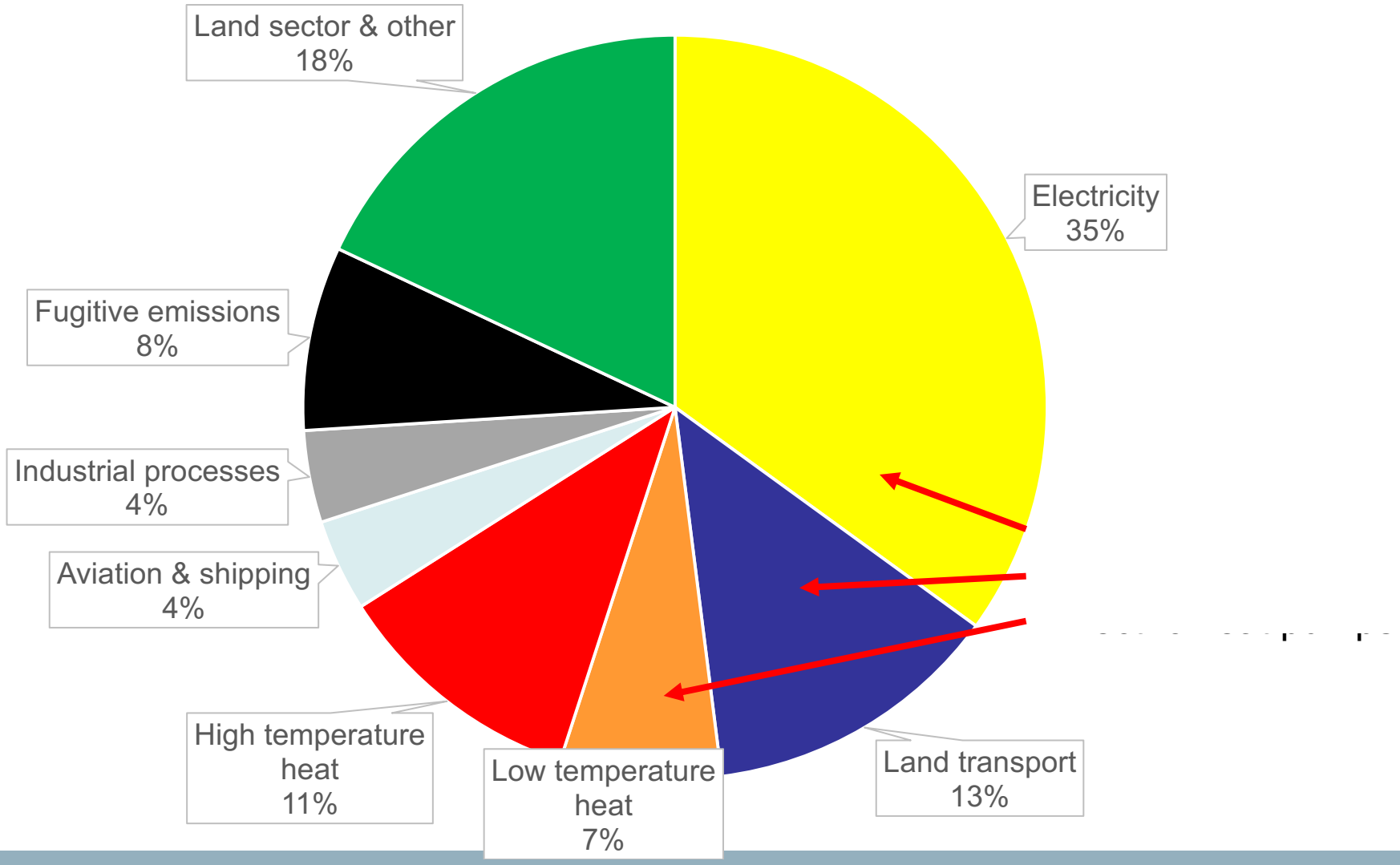
Eliminating emissions, sector by sector



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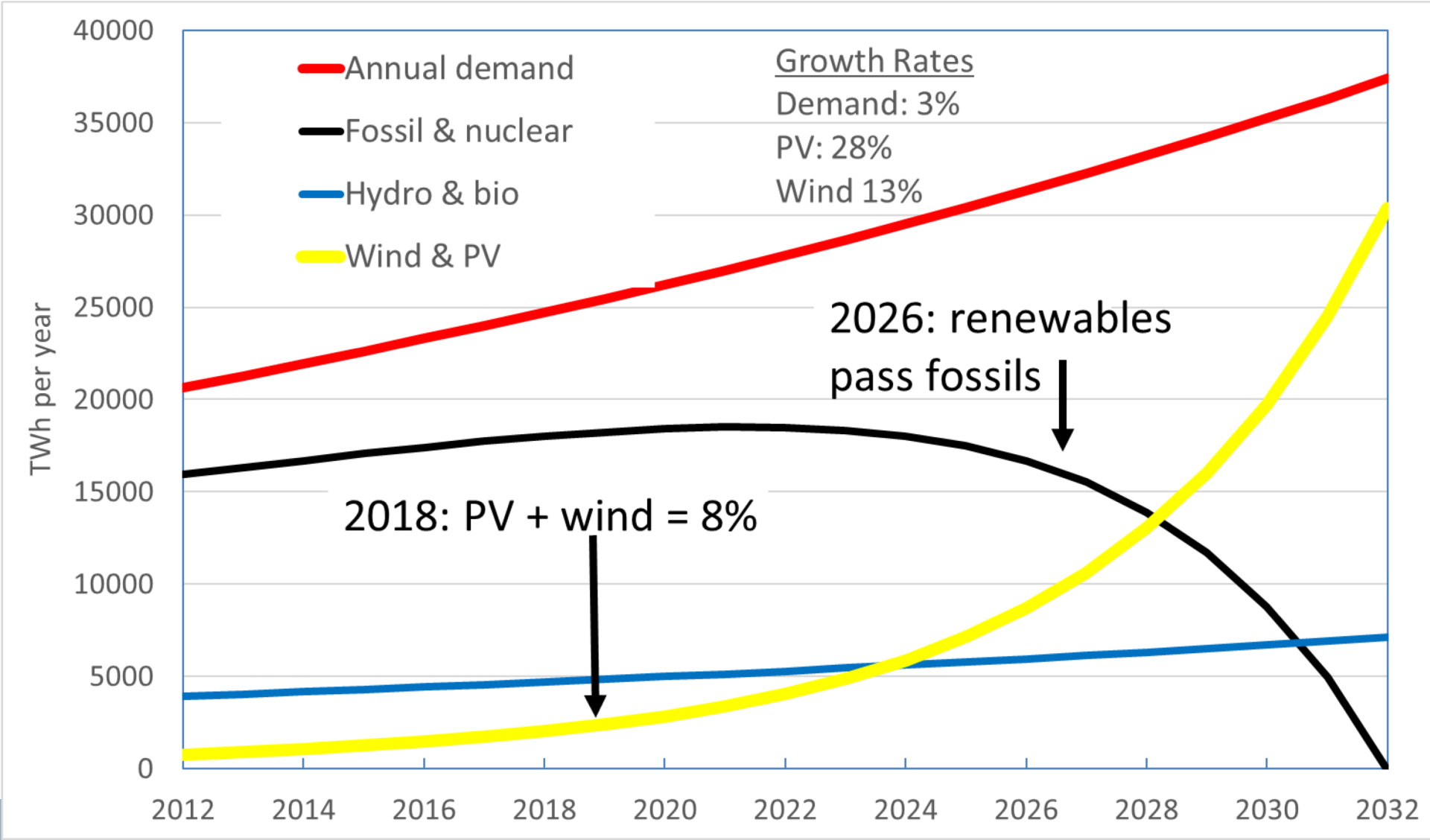
Worldwide electricity supply & demand



Conclusions

- On-track for >70% renewables by 2030 **at zero net cost**
- Storage + HVDC supports a secure grid
- Effectively unlimited number of PHES sites
- PV + wind enables rapid decarbonisation
  - Deep cuts (80%) require elimination of fossil fuels
  - Variable PV and wind must do the heavy lifting
  - Electrify almost everything
- Vast opportunities for storage worldwide

ARENA support gratefully acknowledged