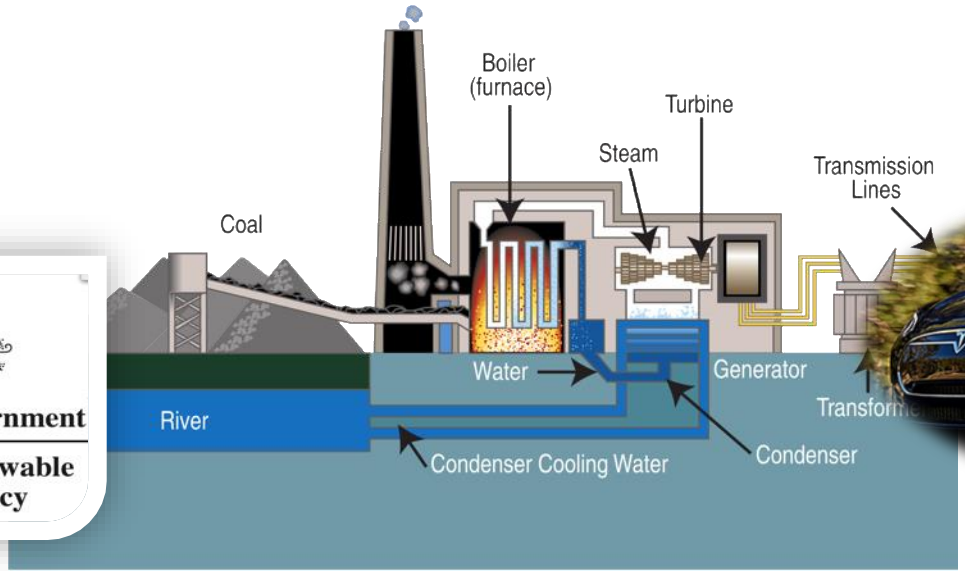
UNSW SYDNEY | Australia's Global University

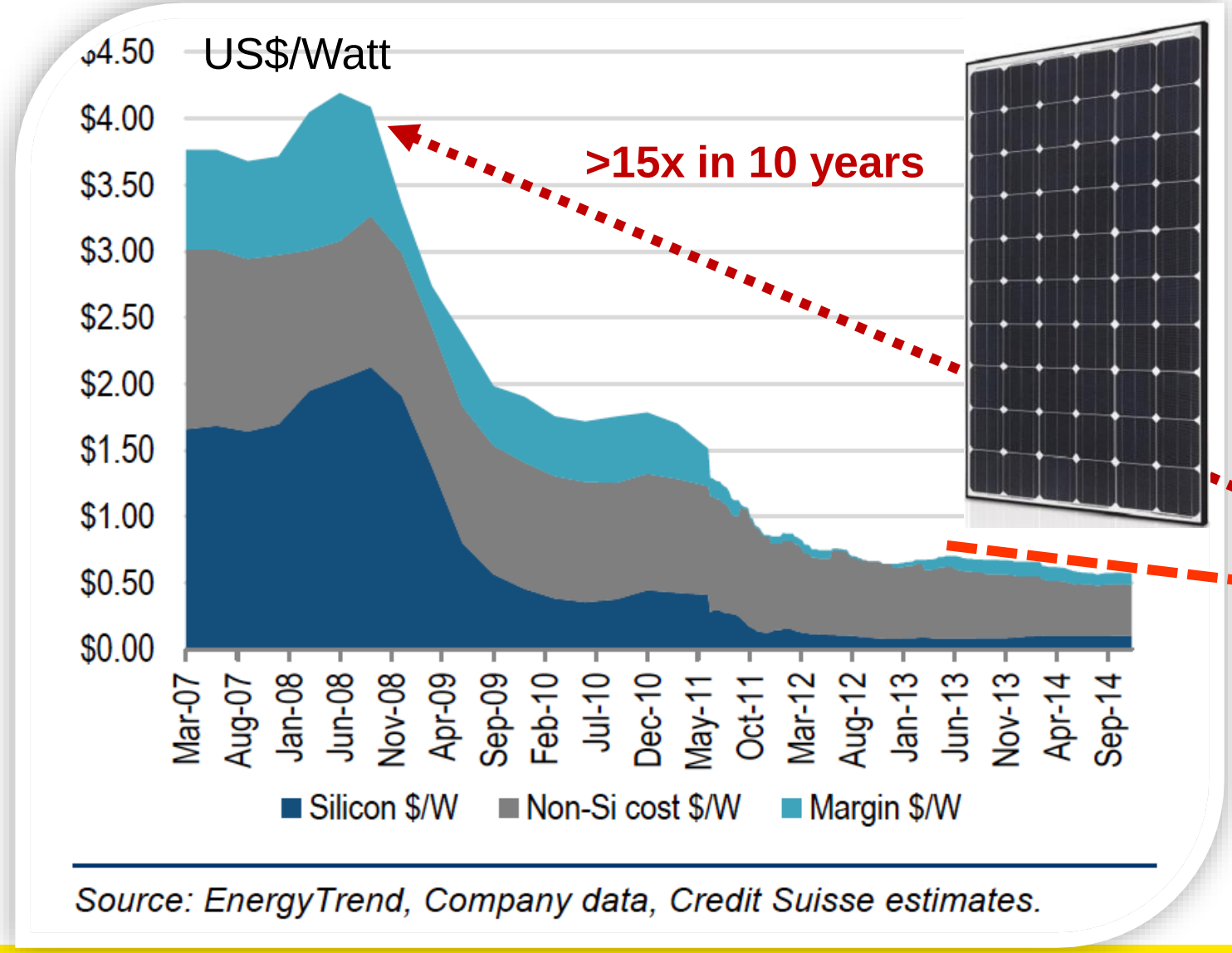
"Can Photovoltaics Provide a Technical Fix to Controlling CO_2 Emissions?"

Martin A. Green, UNSW Sydney



ARENA
Australian Government
Australian Renewable Energy Agency

Recent cost reductions



Low Bids: International Electricity Auctions

PV now cheapest!

Electricity price (US$/MWh)

100
80
60
40
20
0

2014
2015
2016
2017
2018

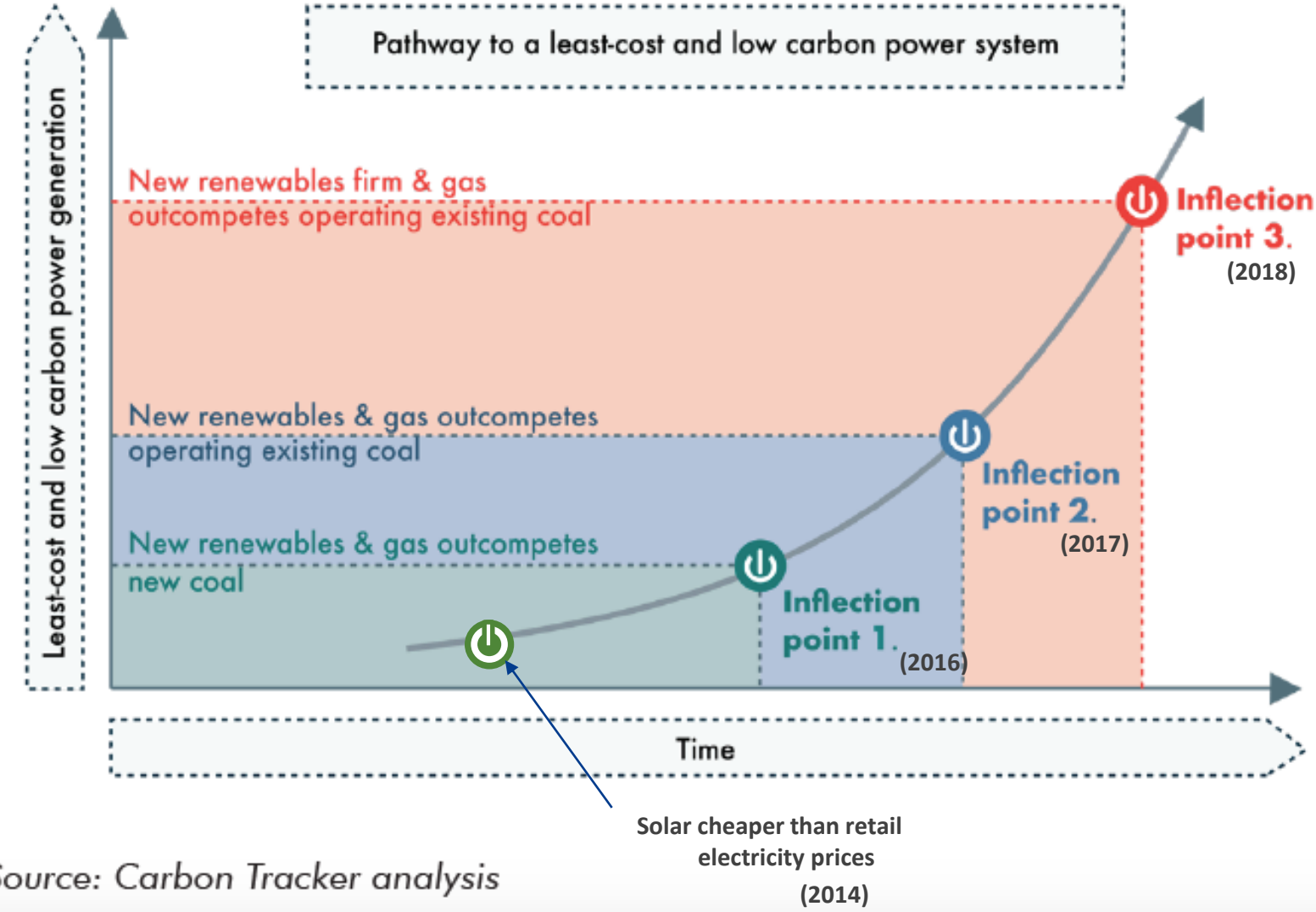
Chile
Brazil
Solar
Jordan
Peru
Mexico
UAE
Chile
UAE
Saudi Arabia

Geothermal
Hydro
New Coal Plant
Gas
Wind
Opportunity Cost Coal @ US$60/t

IRENA
International Renewable Energy Agency

How low?
$10/MWh?

Economic inflection points to a least-cost and low carbon power generation system



Source: Carbon Tracker analysis

RENEW ECONOMY

Fair Dinkum Power News & Analysis

Snowy Hydro smashes price benchmarks for "fair dinkum" wind and solar

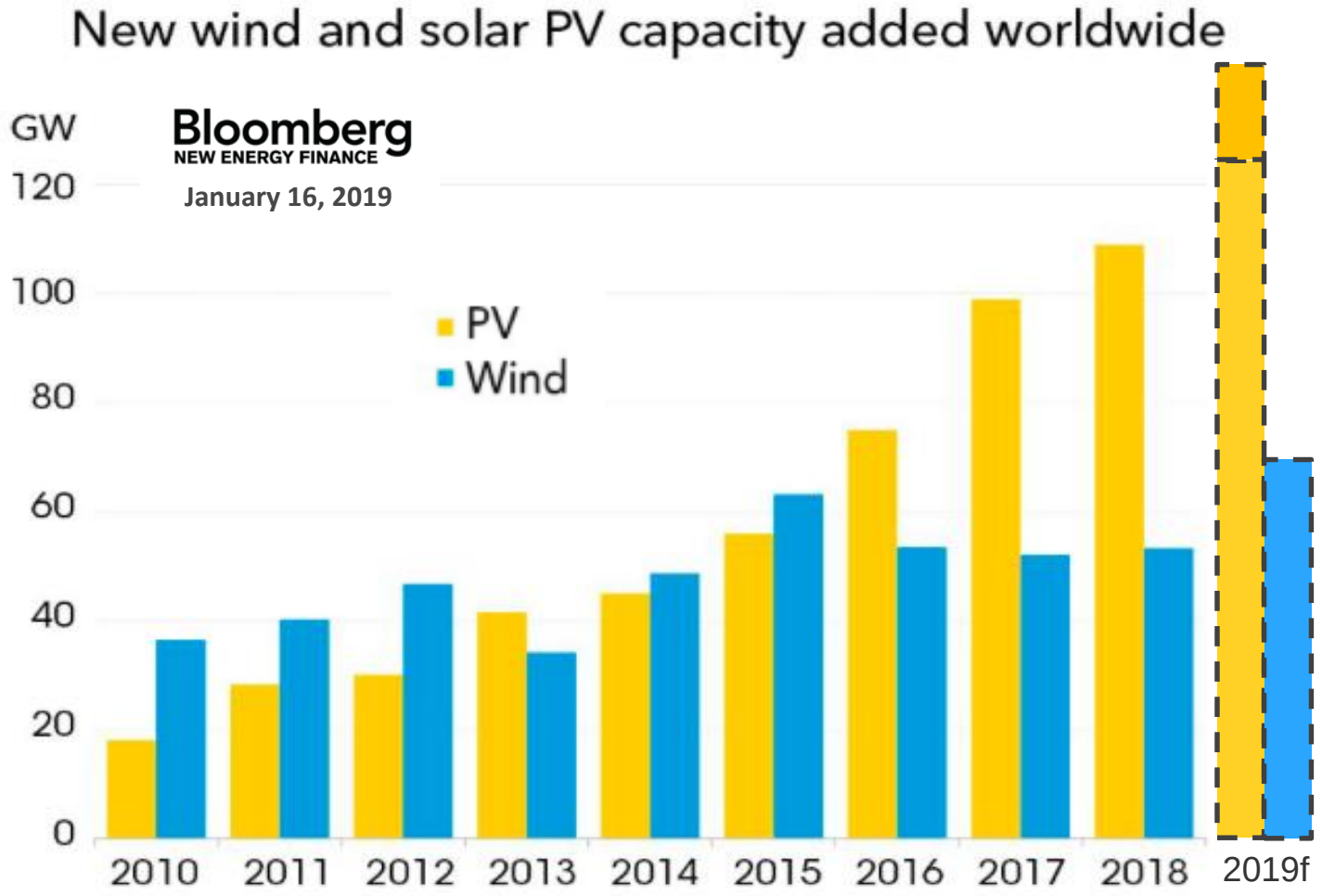
Giles Parkinson 2 November 2018 43 Comments Share

Snowy says cost of "firm" wind and solar significantly below current base-load prices

Giles Parkinson 23 October 2018 32 Comments Share

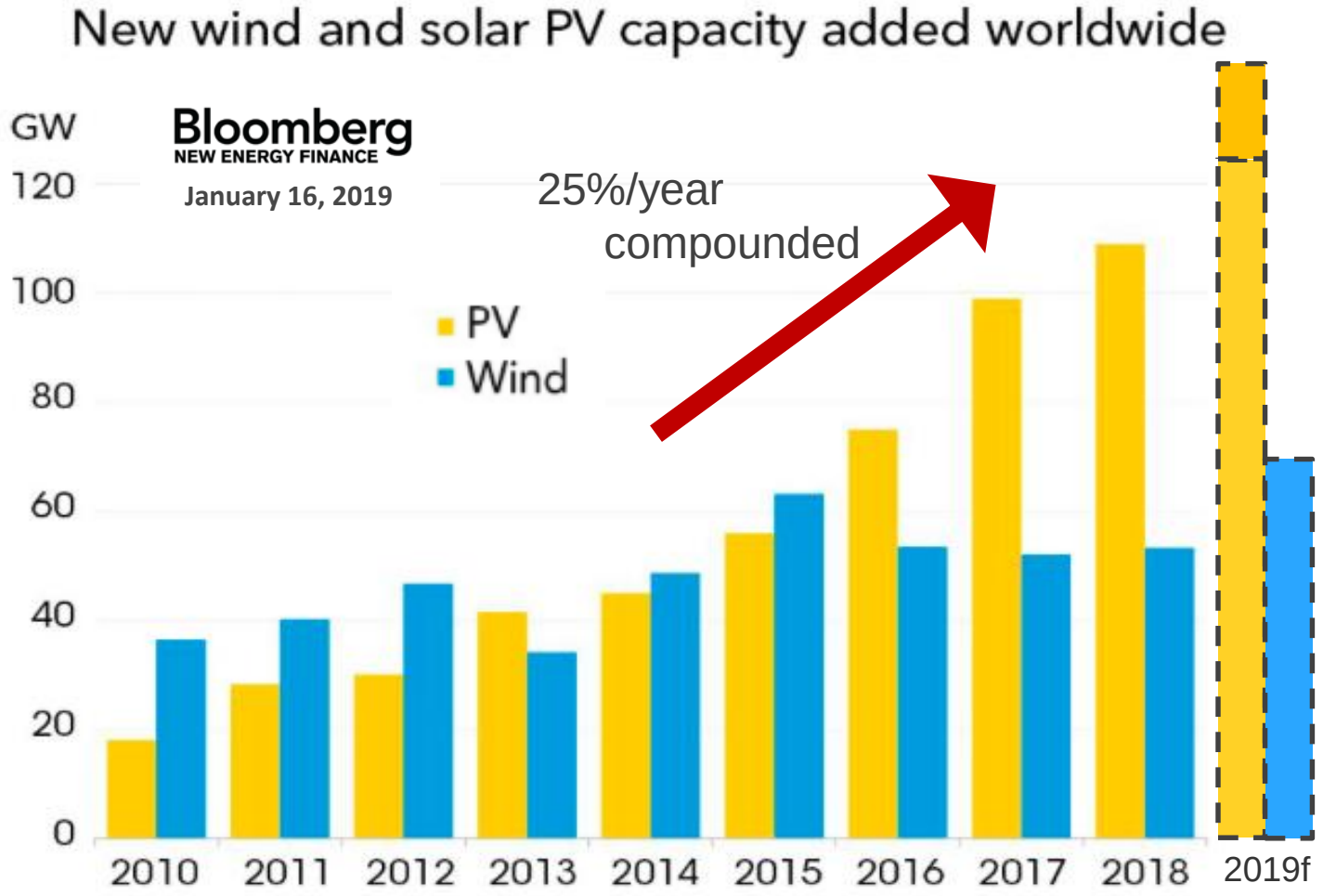
"The renewable energy we have contracted will enable Snowy Hydro to offer very competitive, firm wholesale prices (ie. the cost of the raw renewable energy plus the cost of 'firming') – for below $70/MWh for a flat load, for up to 15 years."

PV market growing (> 0.1 TW in 2018)



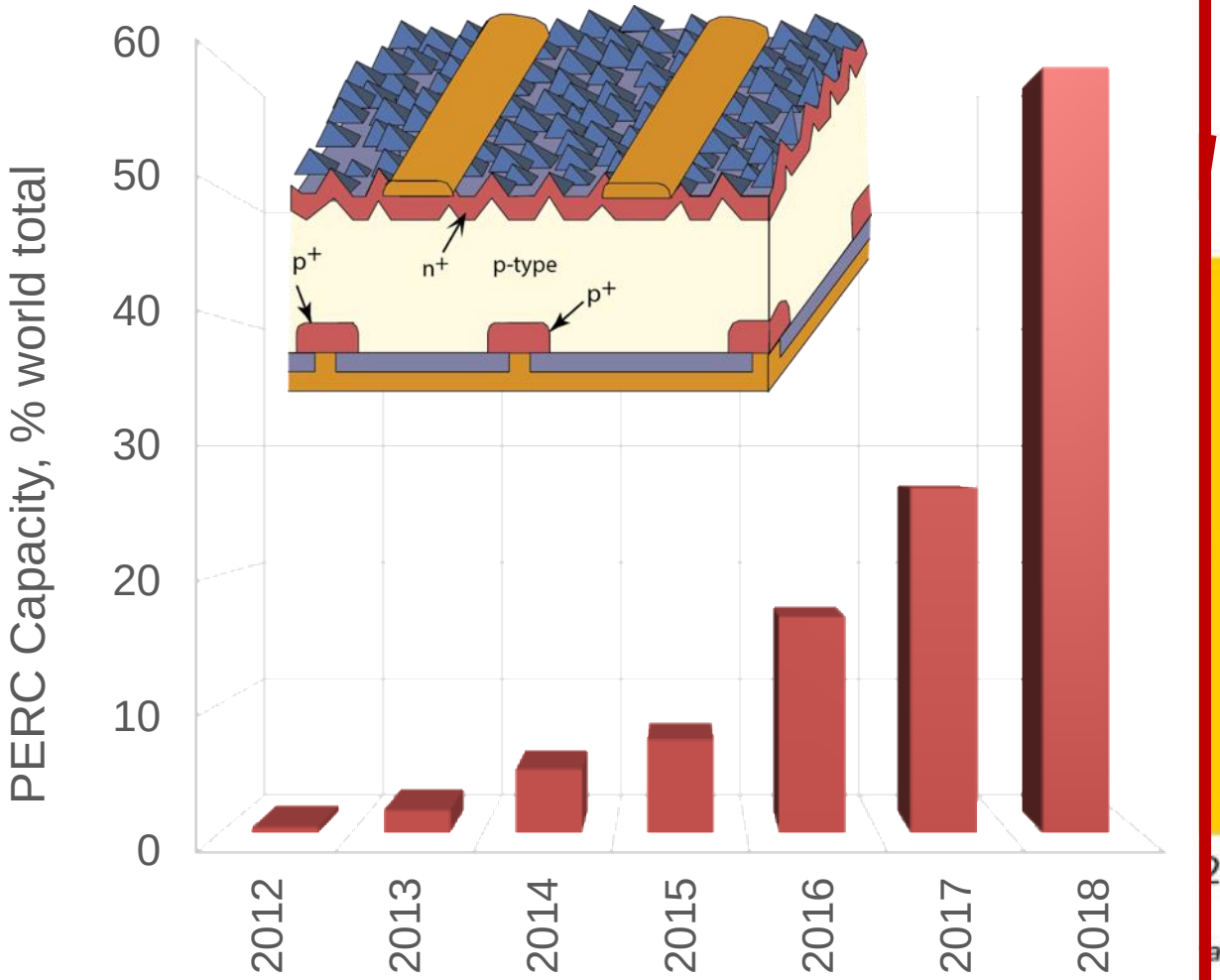
Source: BloombergNEF. Note that the capacity added figures in this chart are preliminary estimates.

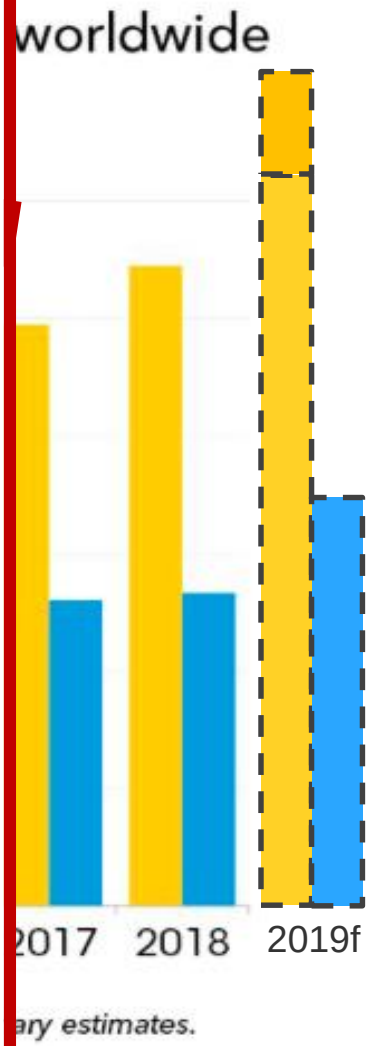
PV market growing (> 0.1 TW in 2018)



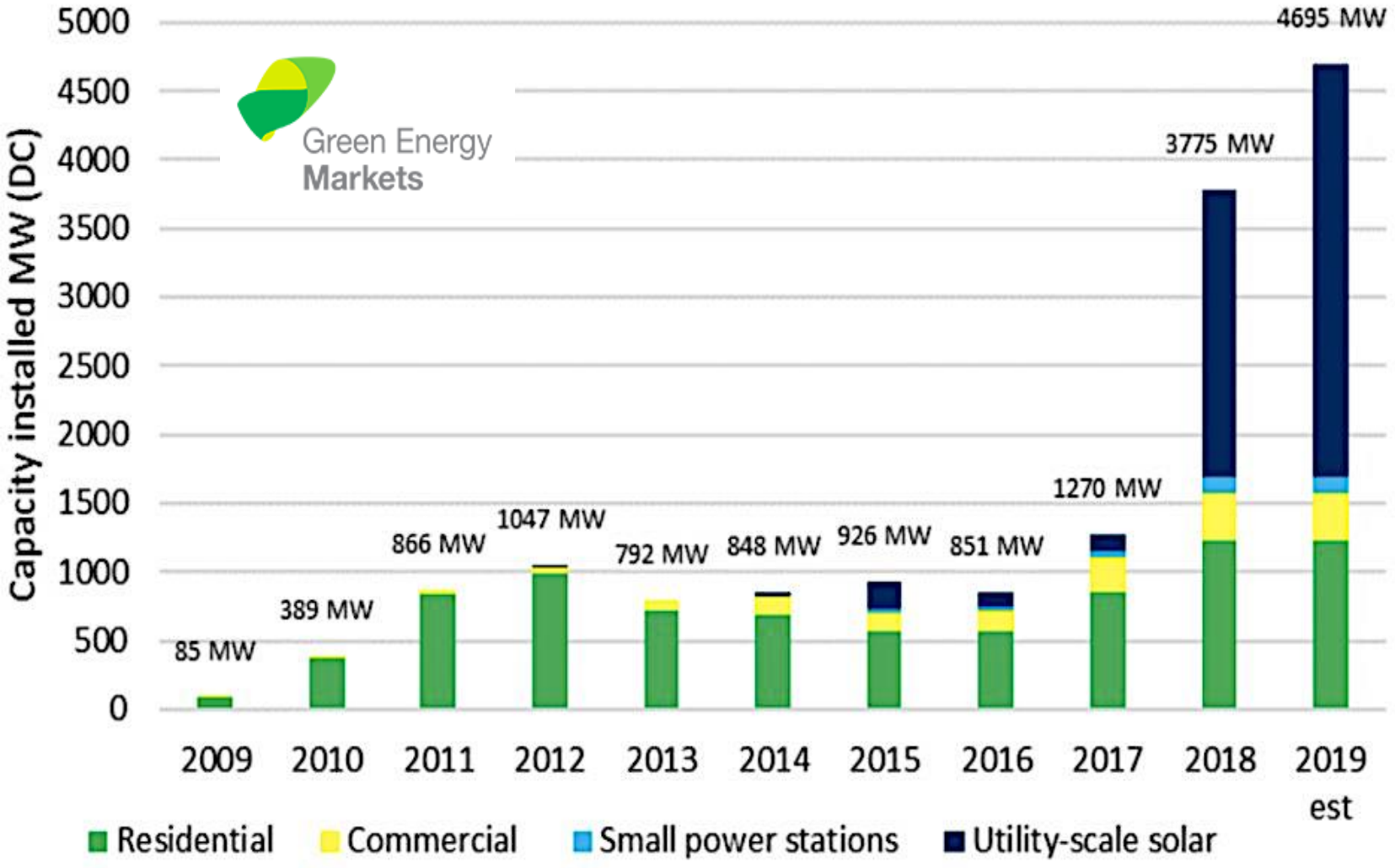
Source: BloombergNEF. Note that the capacity added figures in this chart are preliminary estimates.

PV market growing (> 0.1 TW in 2018)

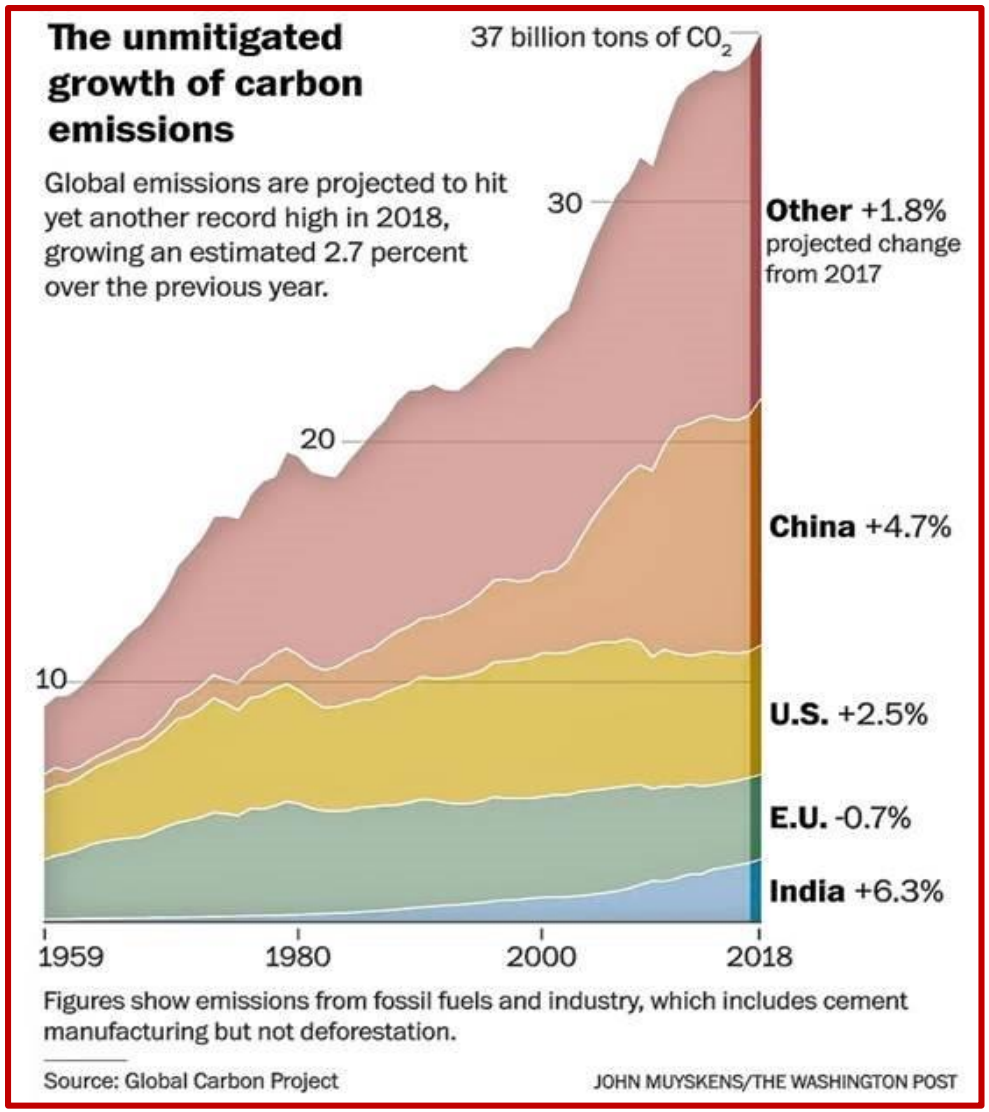




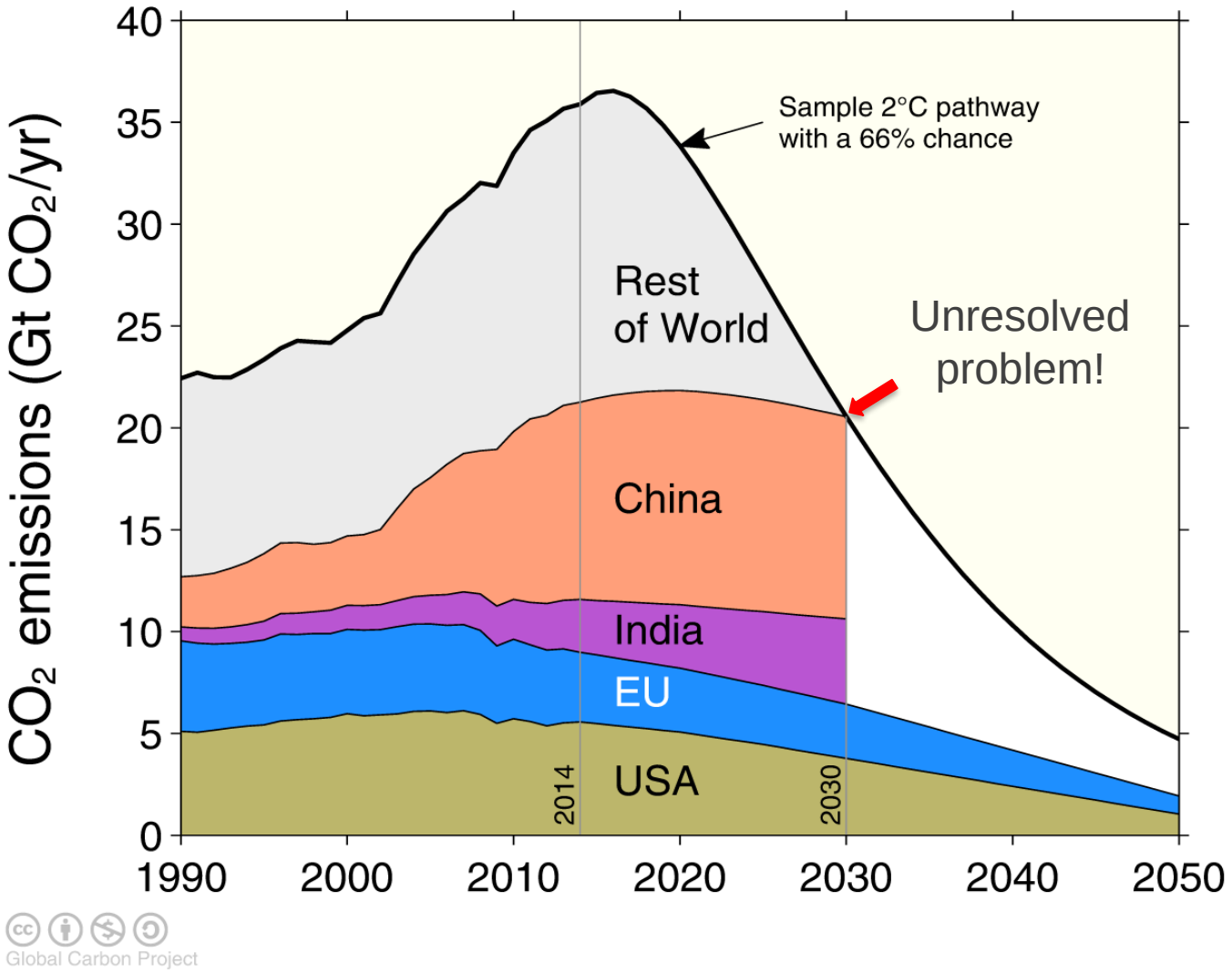
Solar PV capacity installed in Australia (MW DC)



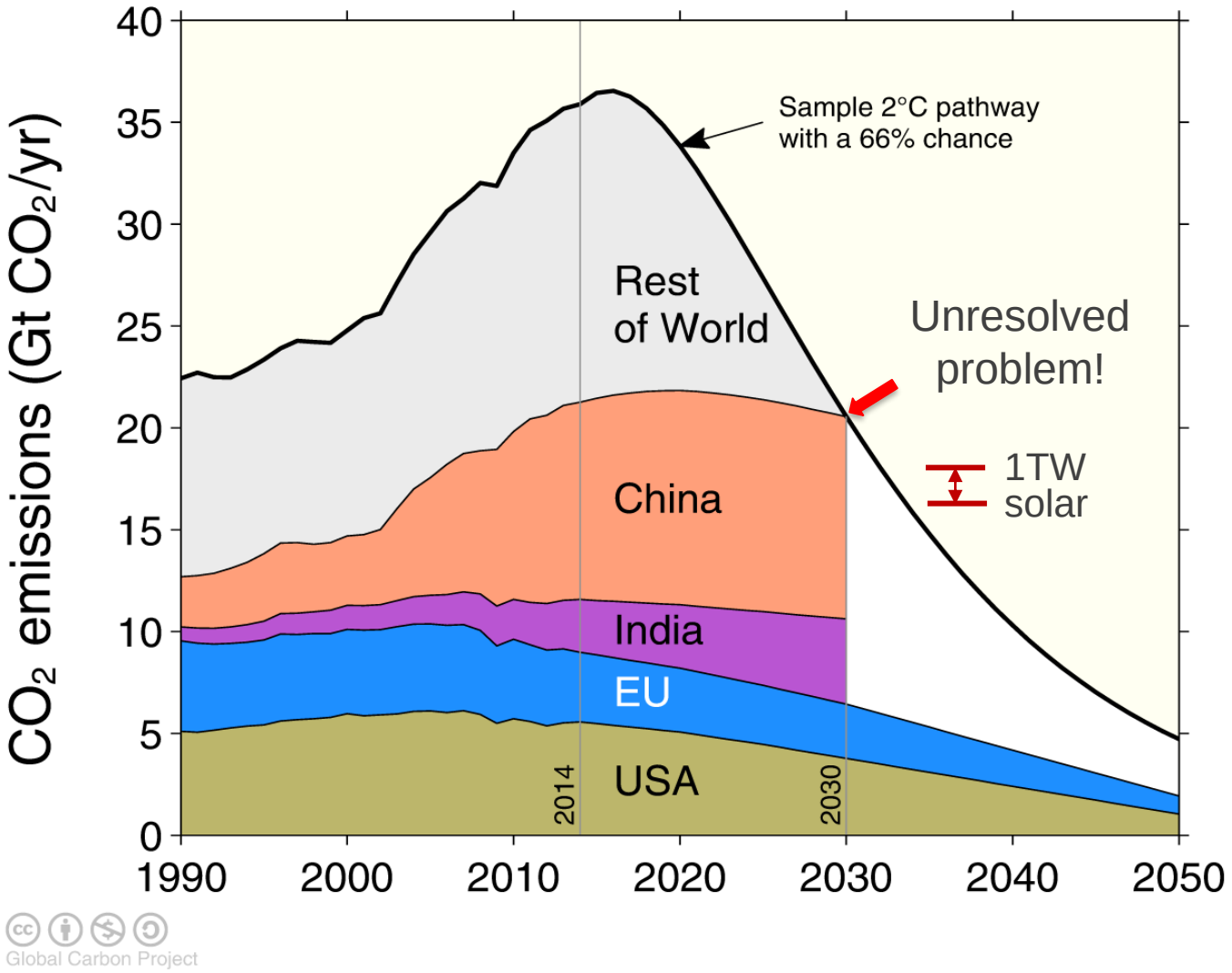
Global CO2 emissions



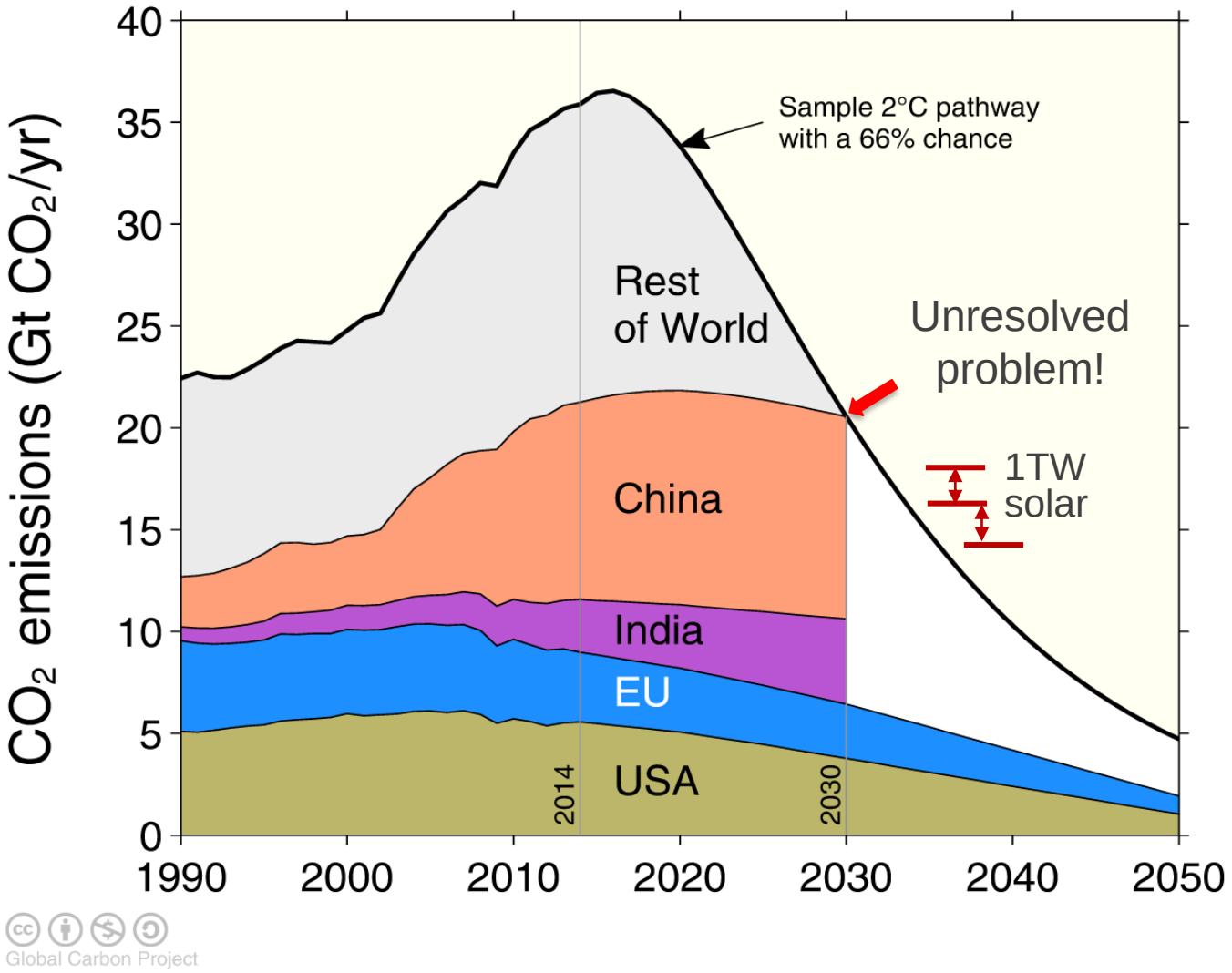
2ºC trajectory



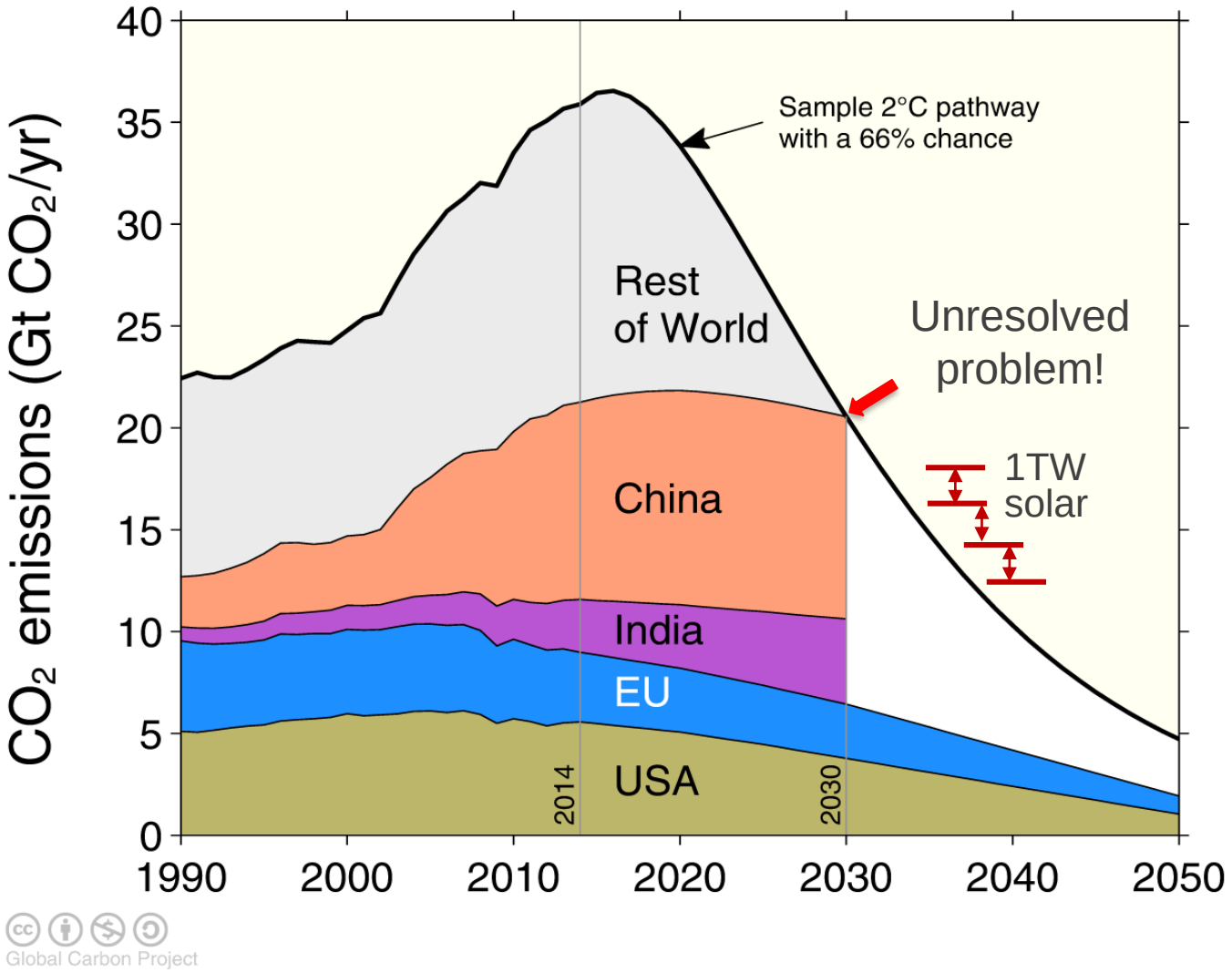
2ºC trajectory



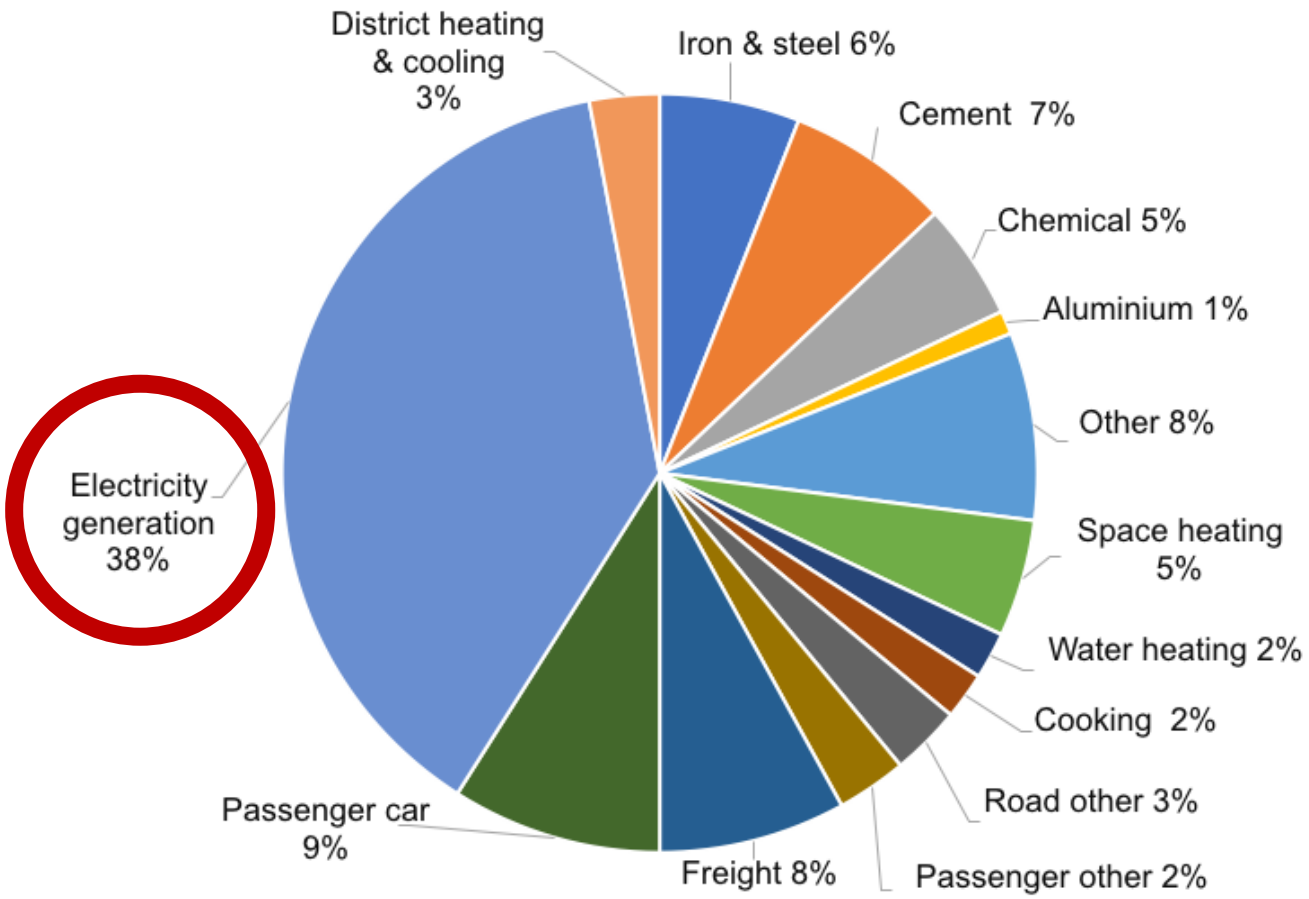
2ºC trajectory



2ºC trajectory



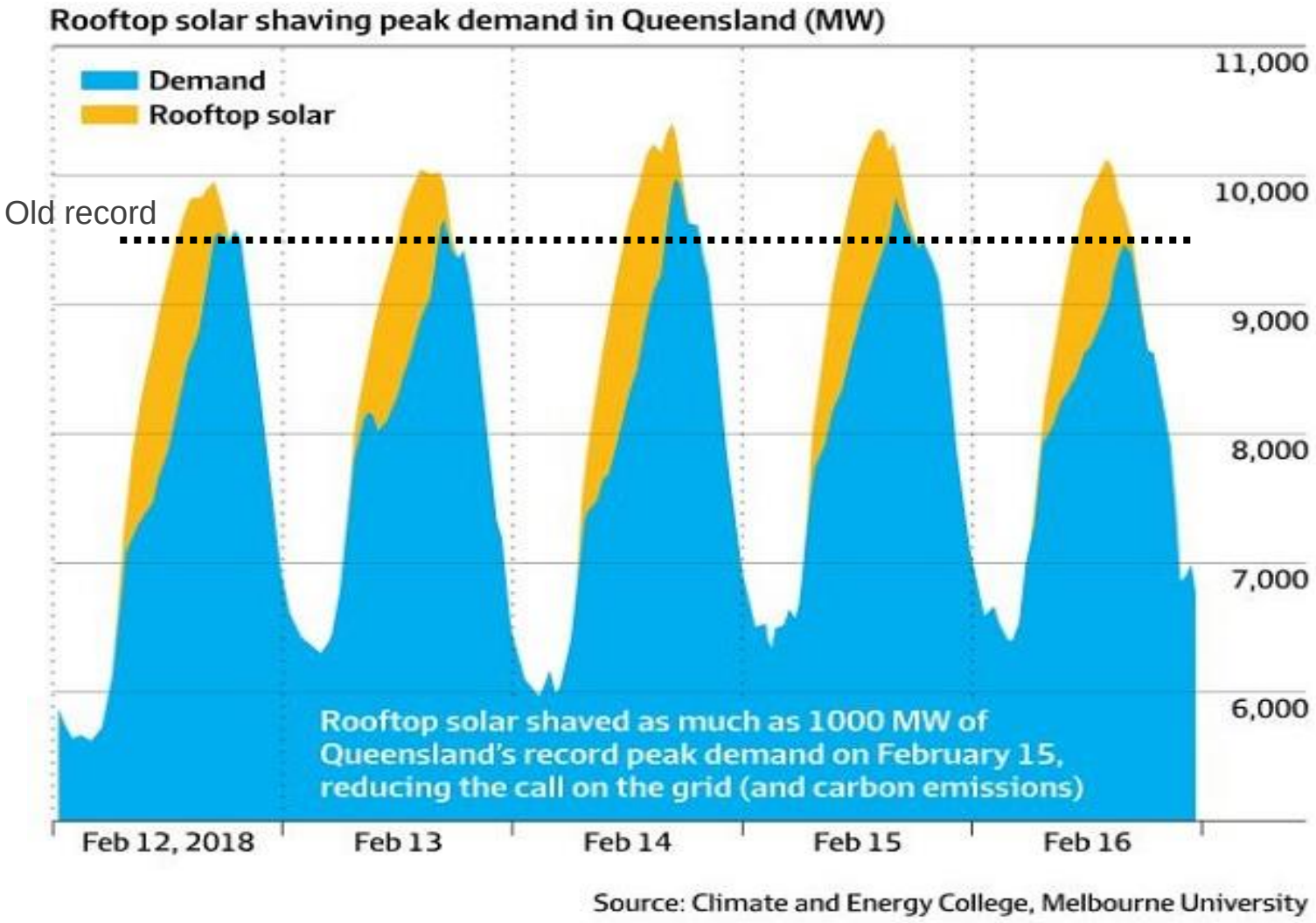
Source of global CO_2 emissions



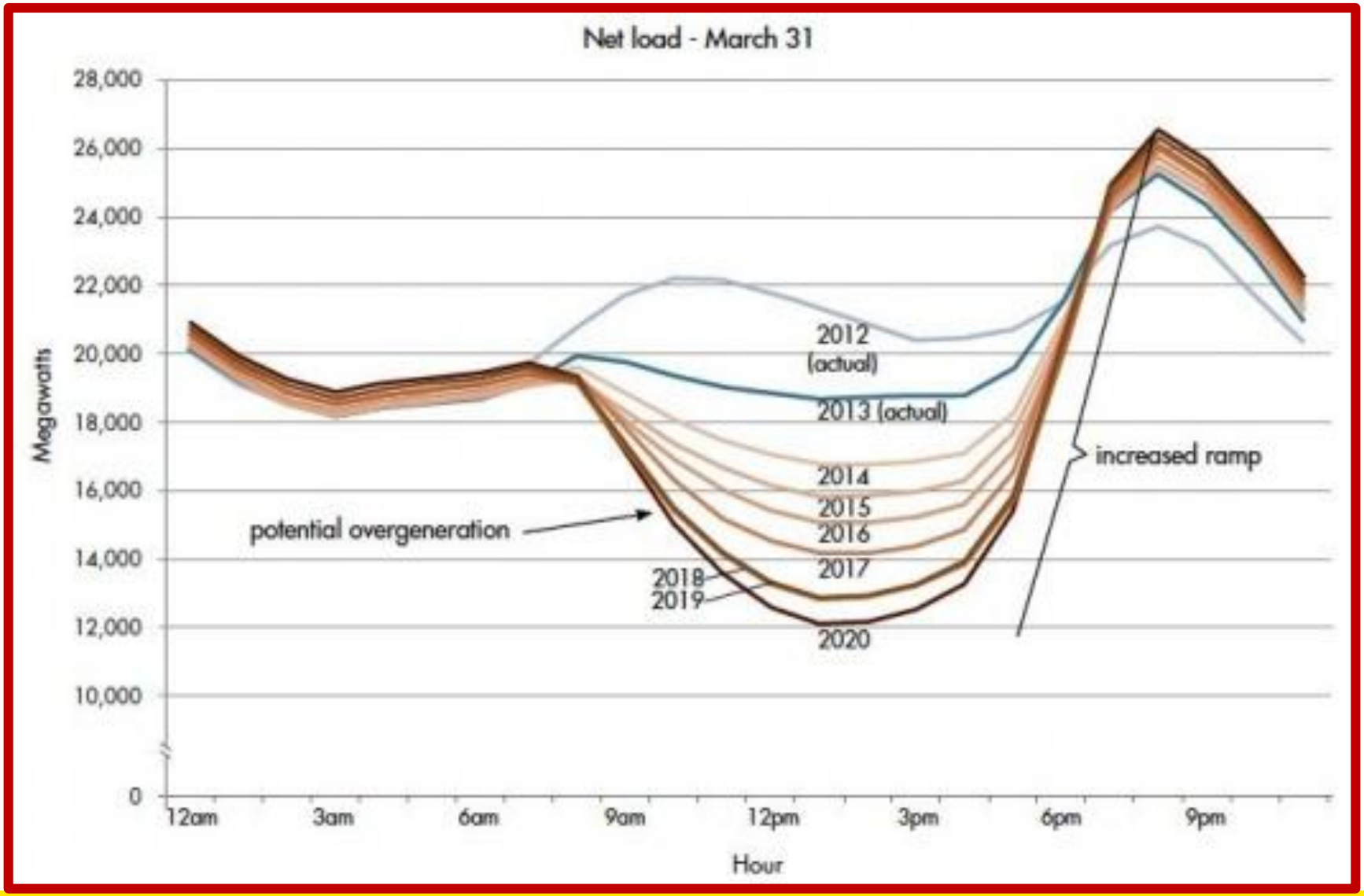
IRENA
International Renewable Energy Agency

UNSW SYDNEY

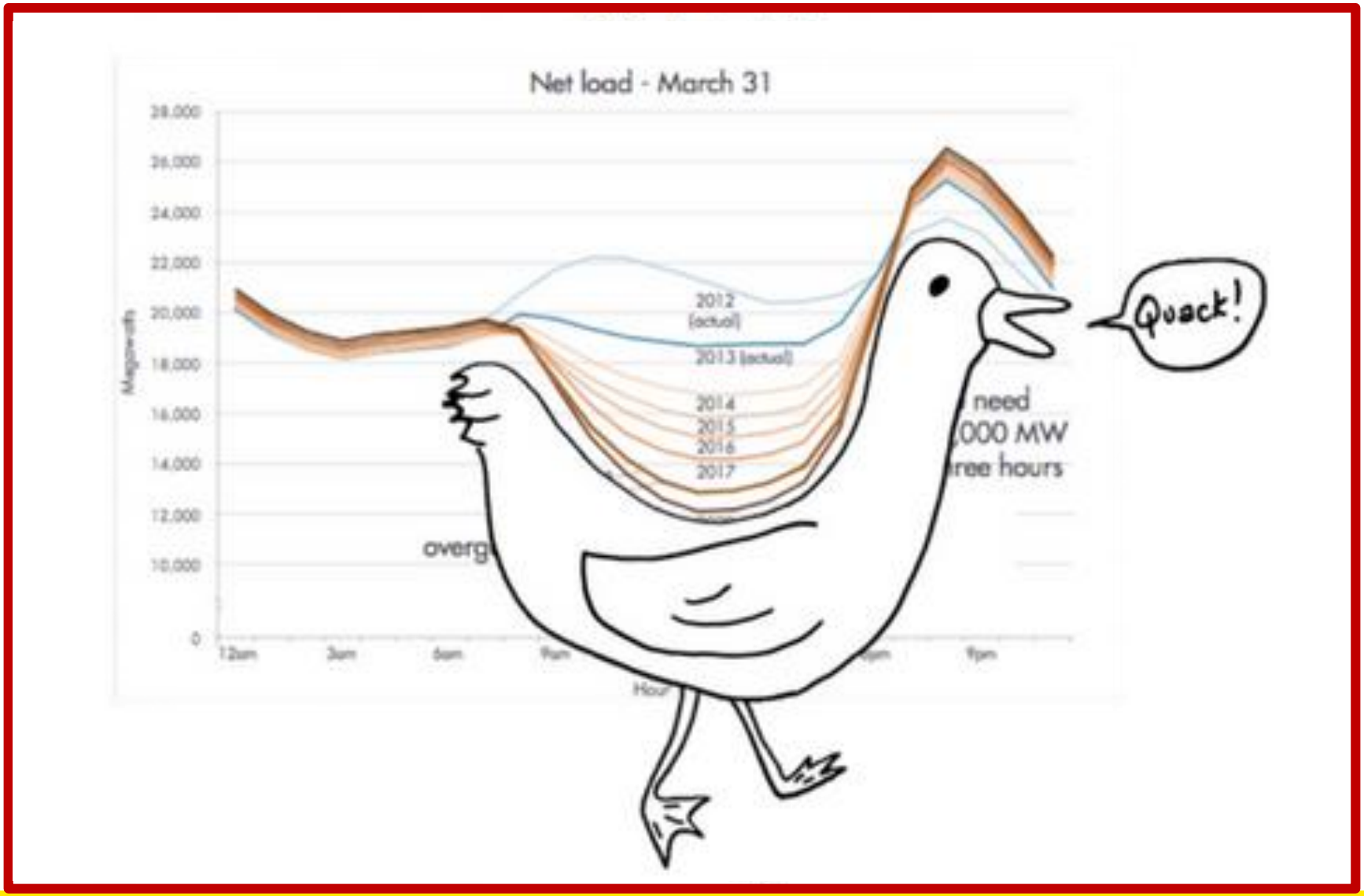
Positive impact for limited solar



“Duck curve”


Net load - March 31
28,000
26,000
24,000
22,000
20,000
18,000
16,000
14,000
12,000
10,000
0
Megawatts
12am
3am
6am
9am
12pm
3pm
6pm
9pm
Hour
2012 (actual)
2013 (actual)
2014
2015
2016
2017
2018
2019
2020
potential overgeneration
increased ramp

“Duck curve”


Net load - March 31
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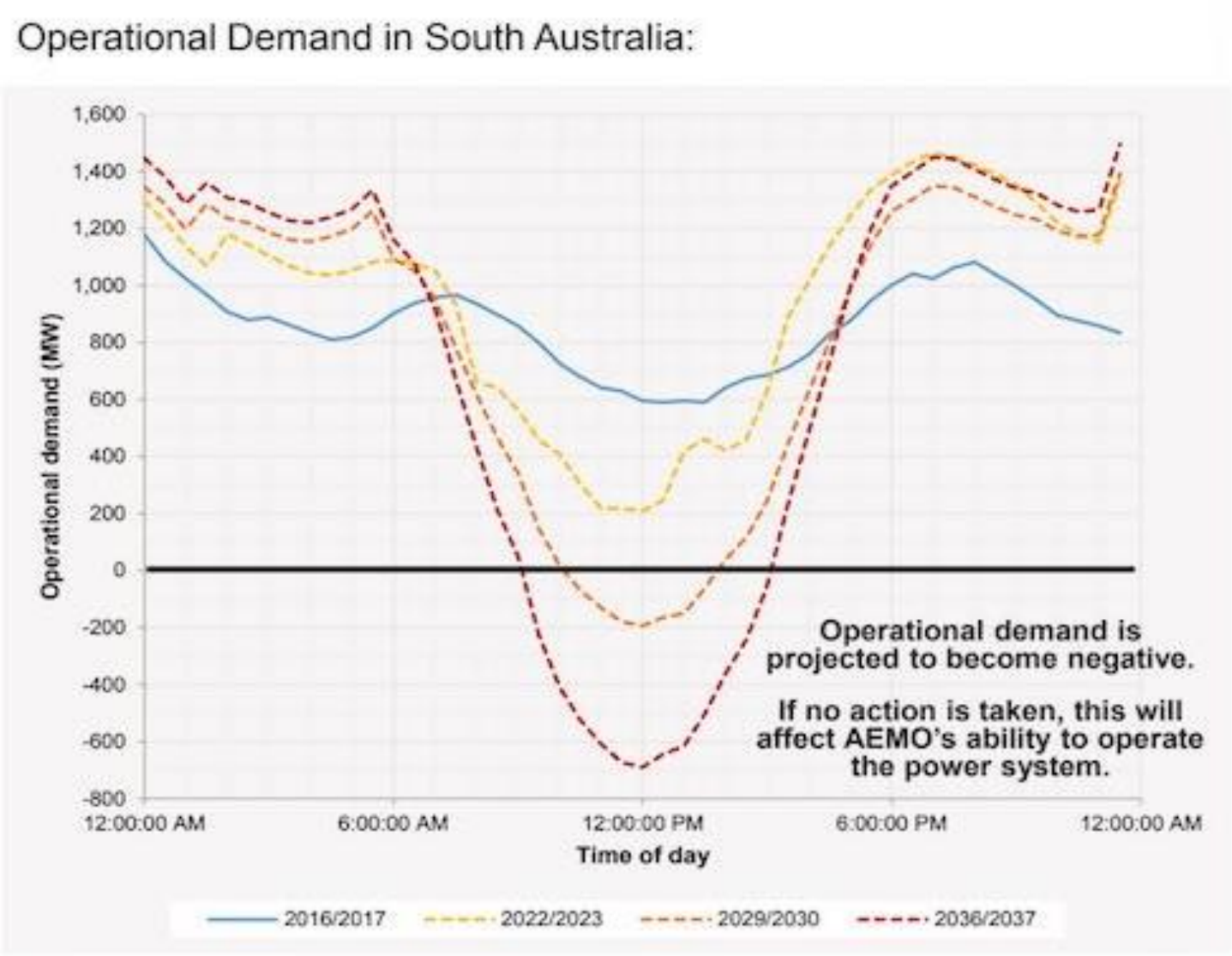
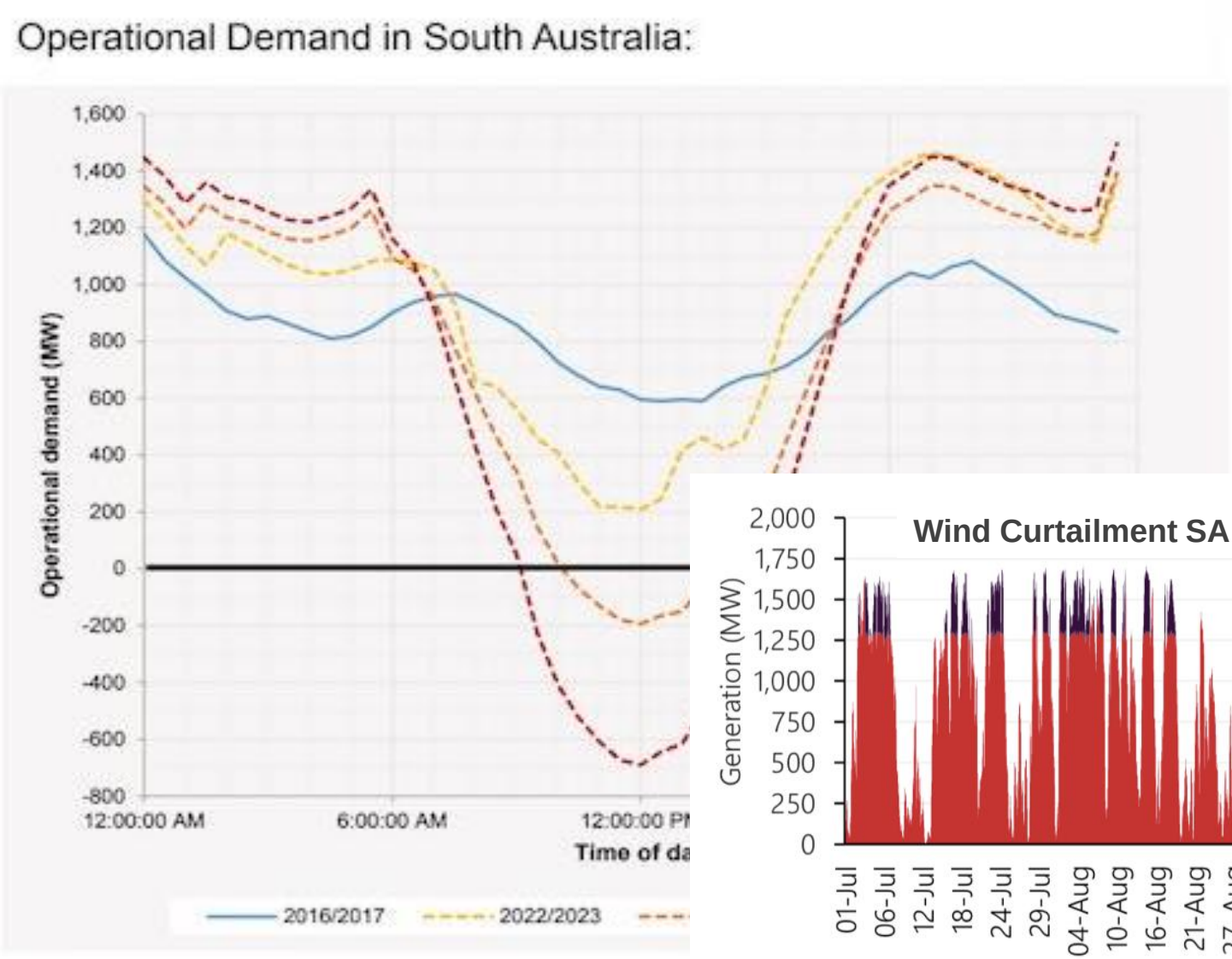
14,000
12,000
10,000
0
Megawatts
12am
3am
6am
9am
9pm
2012 (actual)
2013 (actual)
2014
2015
2016
2017
Quack!
need
000 MW
ree hours

“Duck curve”


Operational Demand in South Australia:
Operational demand (MW)
1,600
1,400
1,200
1,000
800
600
400
200
0
-200
-400
-600
-800
12:00:00 AM
6:00:00 AM
12:00:00 PM
6:00:00 PM
12:00:00 AM
Time of day
Operational demand is projected to become negative.
If no action is taken, this will affect AEMO's ability to operate the power system.
2016/2017
2022/2023
2029/2030
2036/2037

“Duck curve”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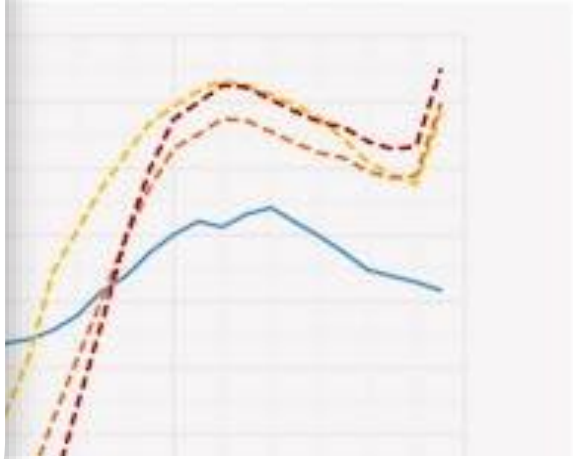
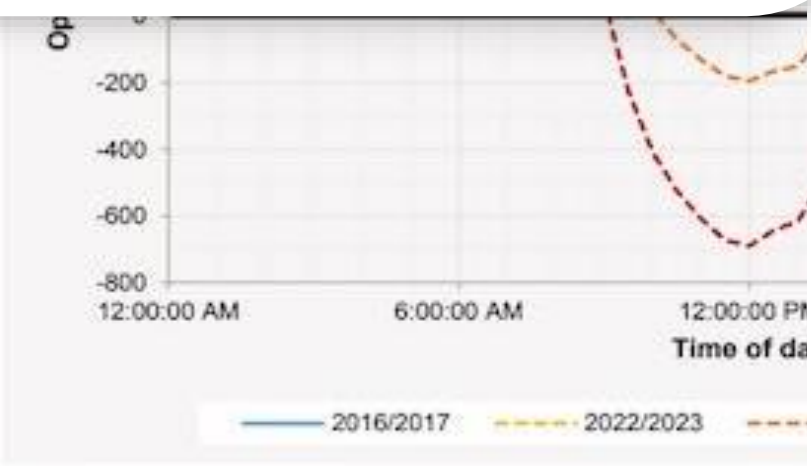
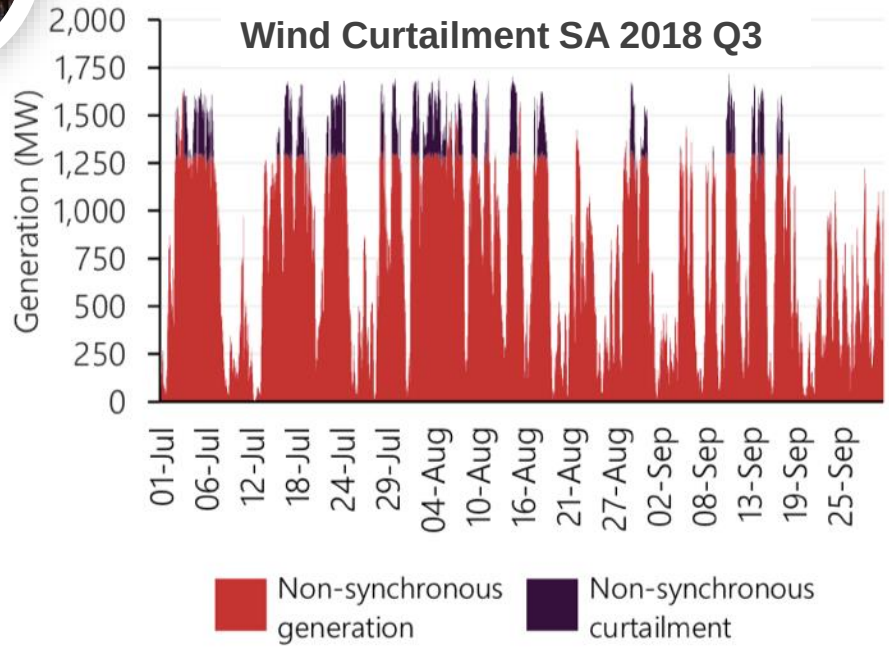
1,200
1,000
800
600
400
200
0
-200
-400
-600
-800
12:00:00 AM
6:00:00 AM
12:00:00 PM
Time of da
2016/2017
2022/2023
Wind Curtailment SA 2018 Q3
Generation (MW)
2,000
1,750
1,500
1,250
1,000
750
500
250
0
01-Jul
06-Jul
12-Jul
18-Jul
24-Jul
29-Jul
04-Aug
10-Aug
16-Aug
21-Aug
27-Aug
02-Sep
08-Sep
13-Sep
19-Sep
25-Sep
Non-synchronous generation
Non-synchronous curtailment

“Duck curve”


© Tim Graham/Corbis




-200
-400
-600
-800
12:00:00 AM
6:00:00 AM
2016/2017
2022/2023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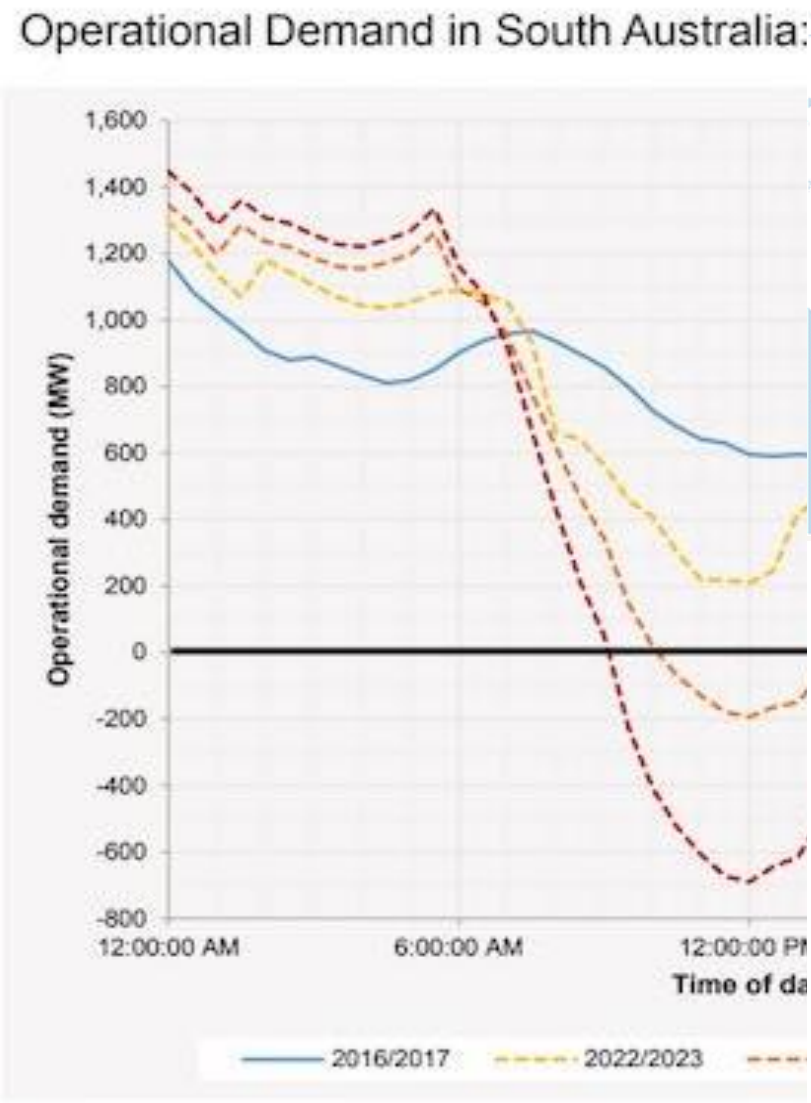
24-Jul
29-Jul
04-Aug
10-Aug
16-Aug
21-Aug
27-Aug
02-Sep
08-Sep
13-Sep
19-Sep
25-Sep
Non-synchronous generation
Non-synchronous curtailment

“Duck curve”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1,200
1,000
800
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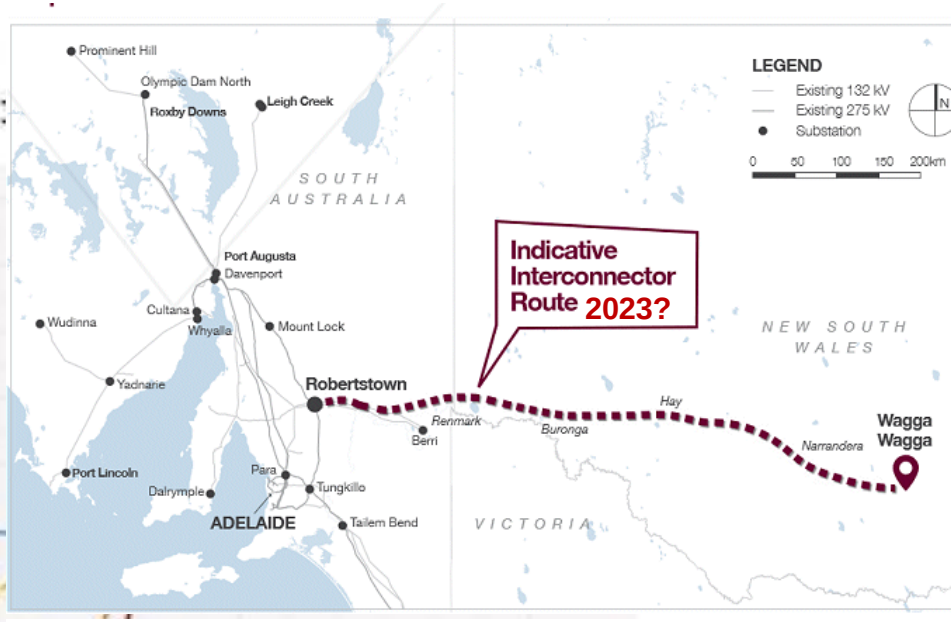
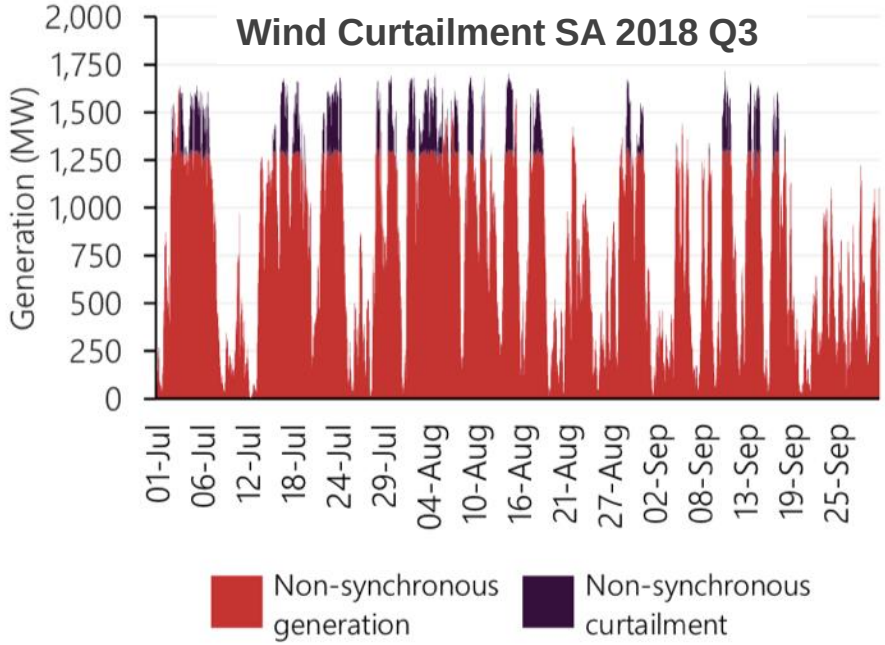
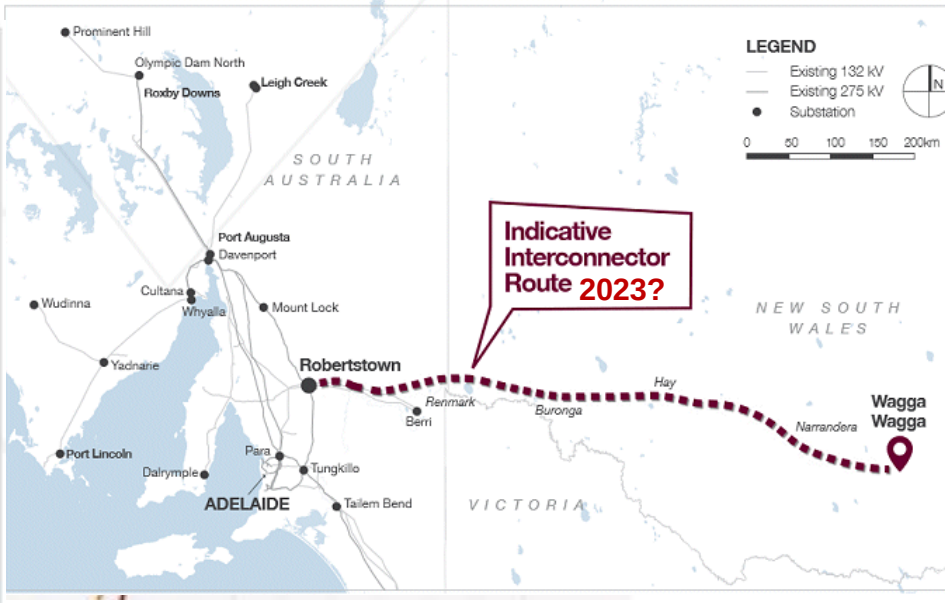
400
200
0
-200
-400
-600
-800
12:00:00 AM
6:00:00 AM
12:00:00 PM
Time of da
2016/2017
2022/2023

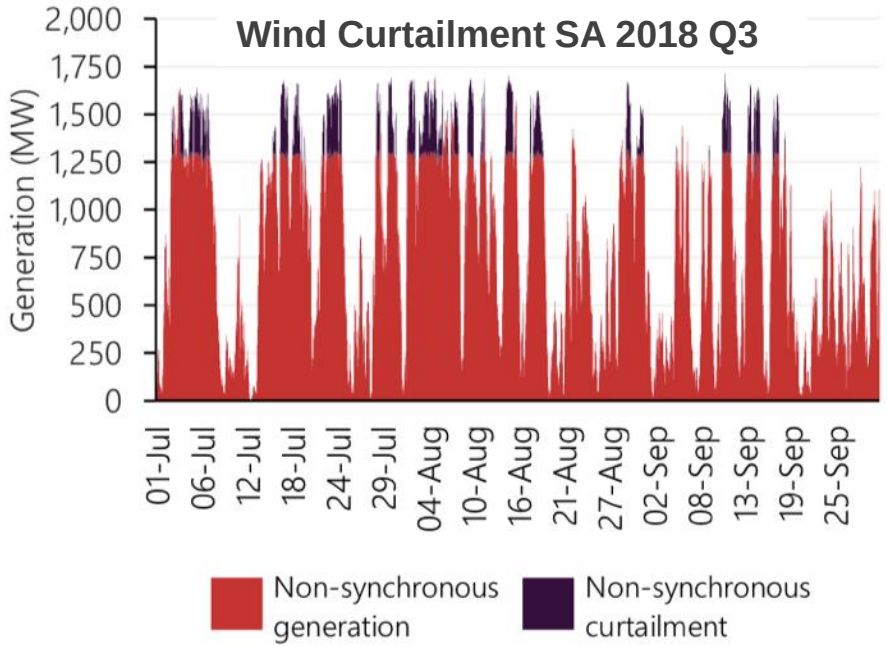

Prominent Hill
Olympic Dam North
Roxby Downs
Leigh Creek
SOUTH AUSTRALIA
Port Augusta
Davenport
Cultana
Whyalla
Mount Lock
Wudinna
Yadnarie
Robertstown
Port Lincoln
Dalrymple
Para
Tungkillo
ADELAIDE
Tailem Bend
VICTORIA
NEW SOUTH WALES
Renmark
Berri
Buronga
Hay
Narrandera
Wagga Wagga
Indicative Interconnector Route 2023?
LEGEND
Existing 132 kV
Existing 275 kV
Substation
0 50 100 150 200km

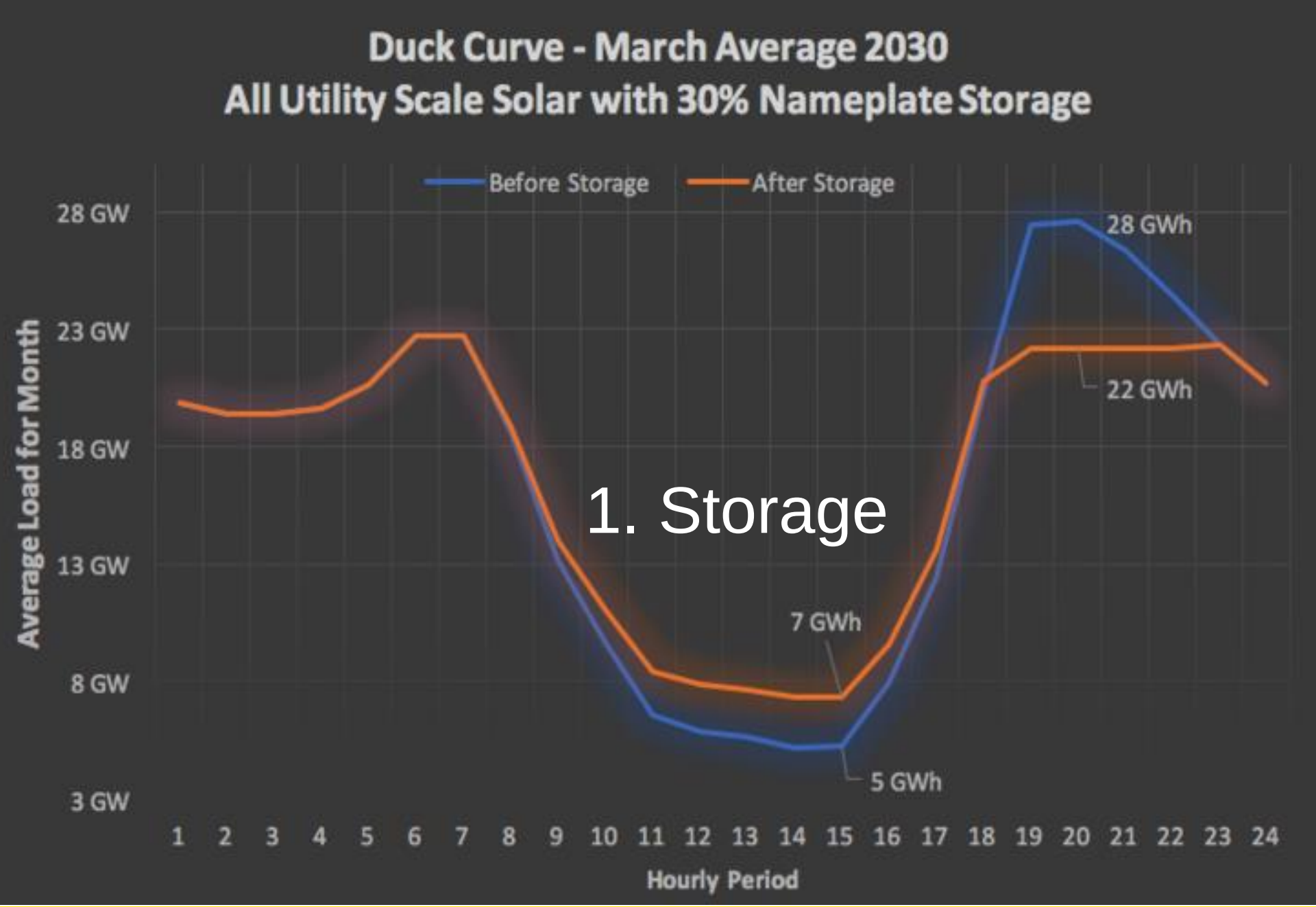

Wind Curtailment SA 2018 Q3
Generation (MW)
2,000
1,750
1,500
1,250
1,000
750
500
250
0
01-Jul
06-Jul
12-Jul
18-Jul
24-Jul
29-Jul
04-Aug
10-Aug
16-Aug
21-Aug
27-Aug
02-Sep
08-Sep
13-Sep
19-Sep
25-Sep
Non-synchronous generation
Non-synchronous curtailment

“Duck curve”

Map of indicative interconnector route

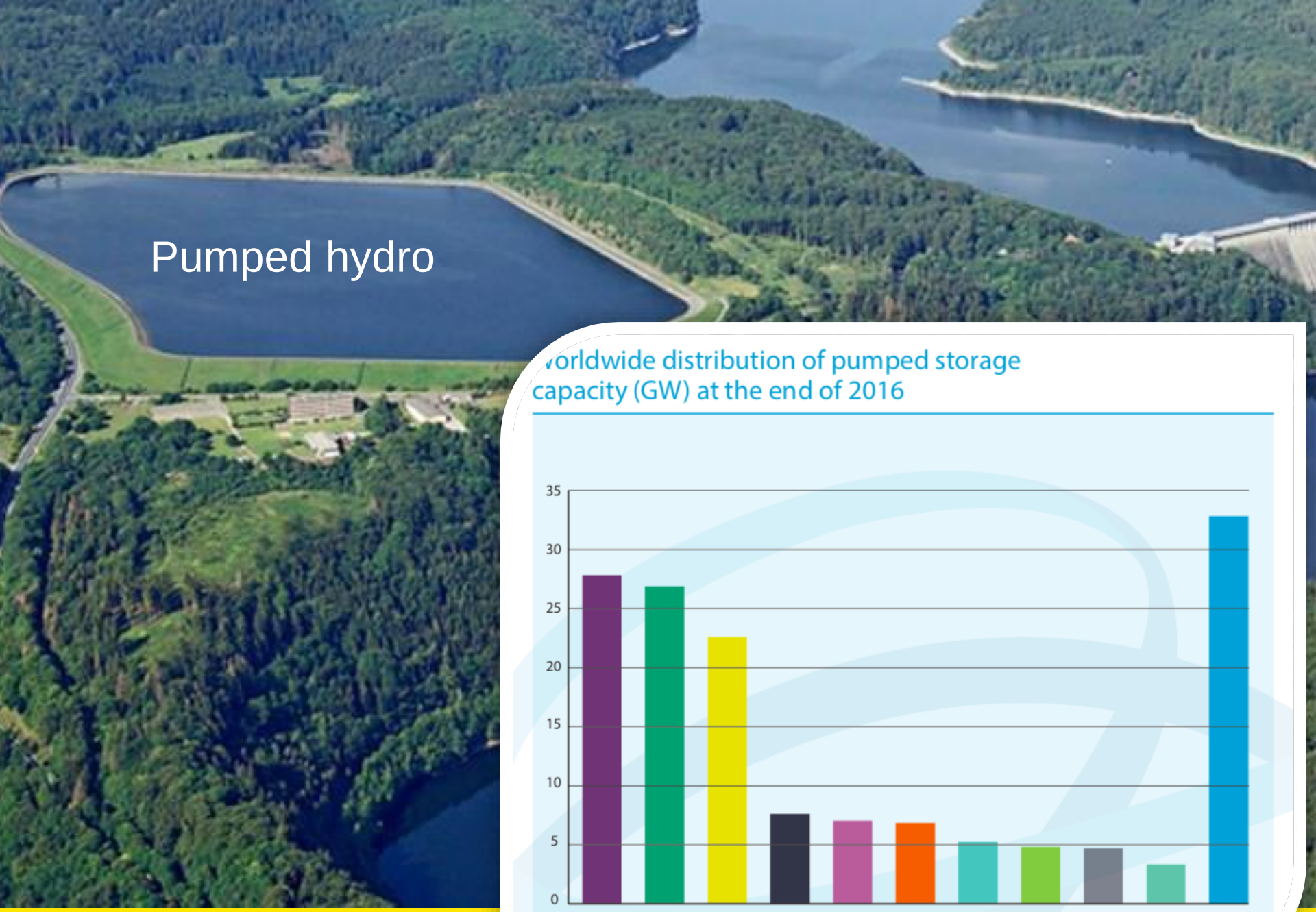





Duck Curve - March Average 2030
All Utility Scale Solar with 30% Nameplate Storage
Before Storage
After Storage
28 GW
23 GW
18 GW
13 GW
8 GW
3 GW
Average Load for Month
28 GWh
22 GWh
7 GWh
5 GWh
1. Storage
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Hourly Period

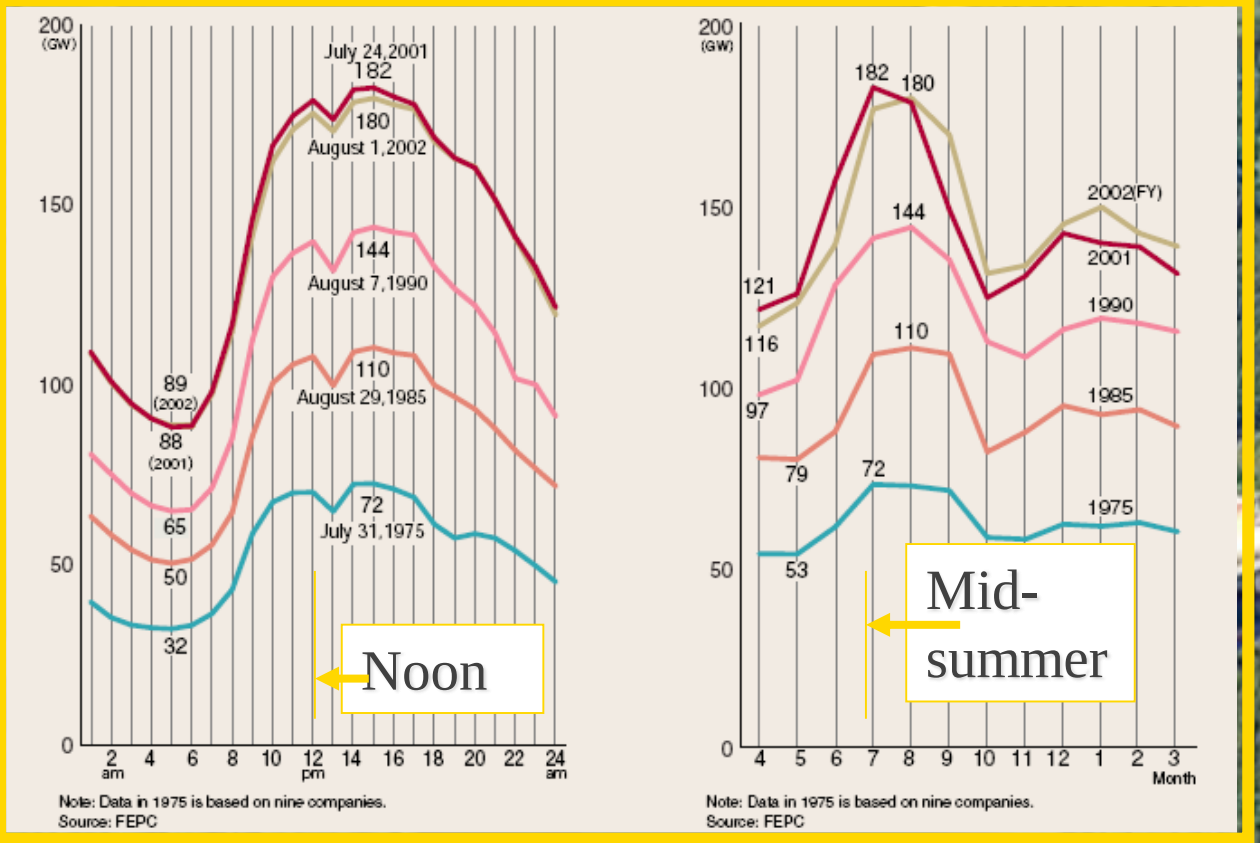

Pumped hydro

Pumped hydro

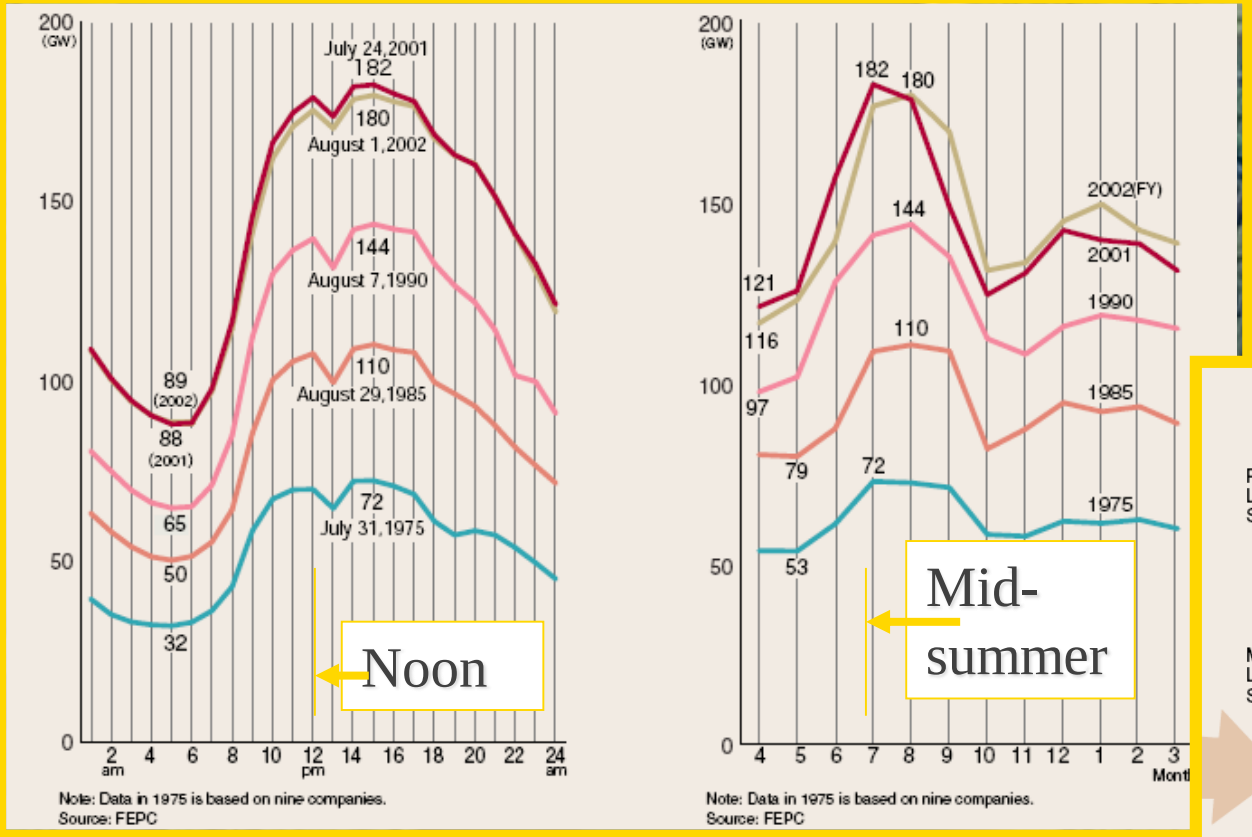


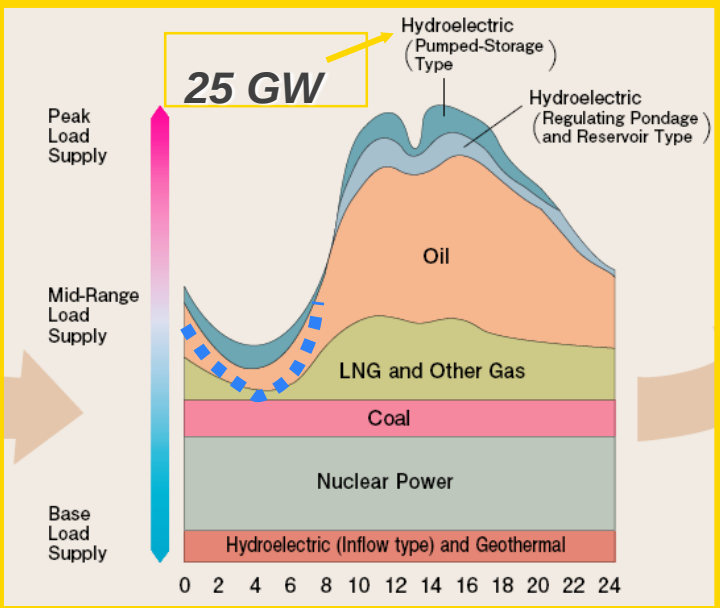
Worldwide distribution of pumped storage capacity (GW) at the end of 2016

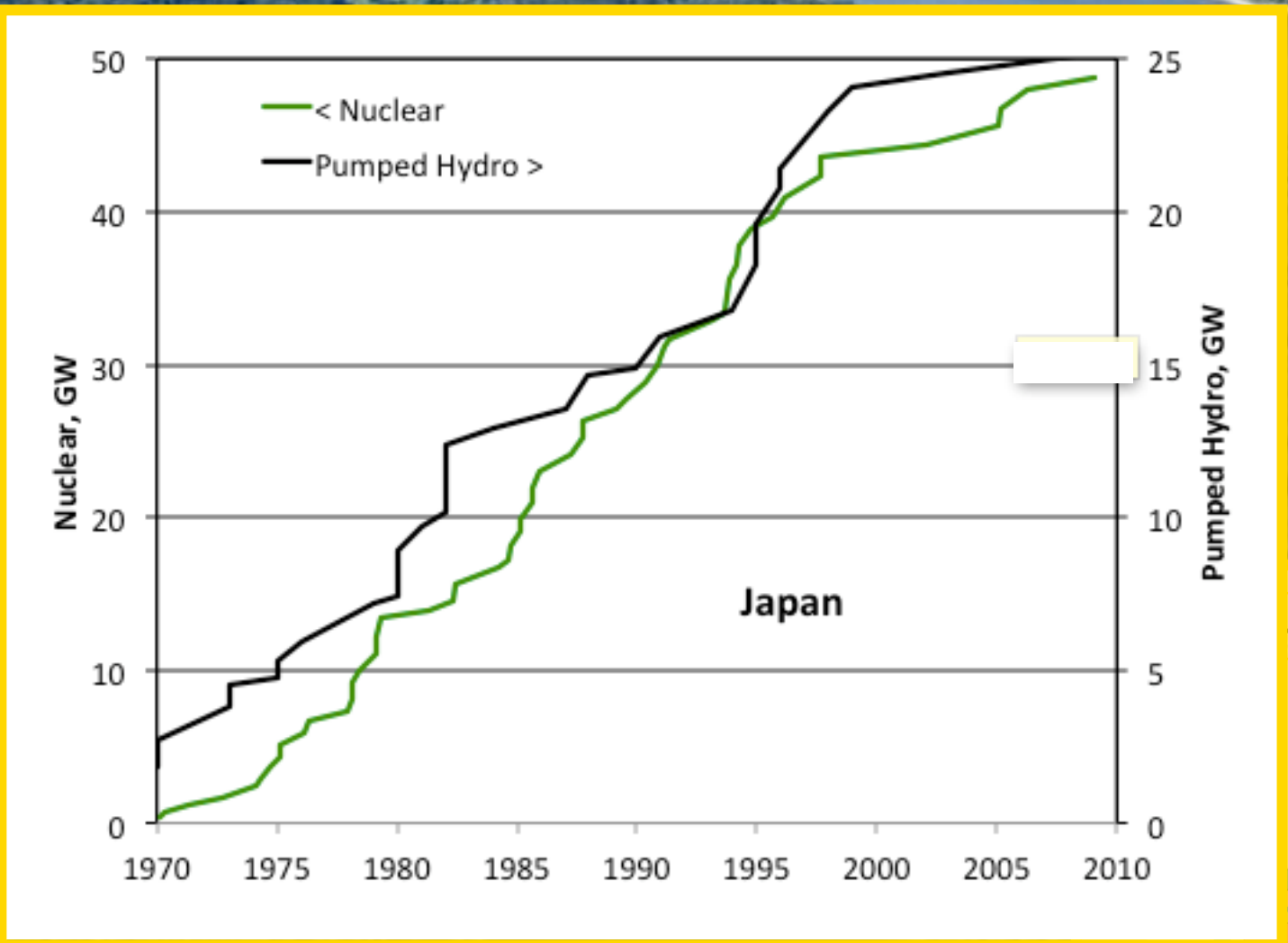
Japan's summer peak

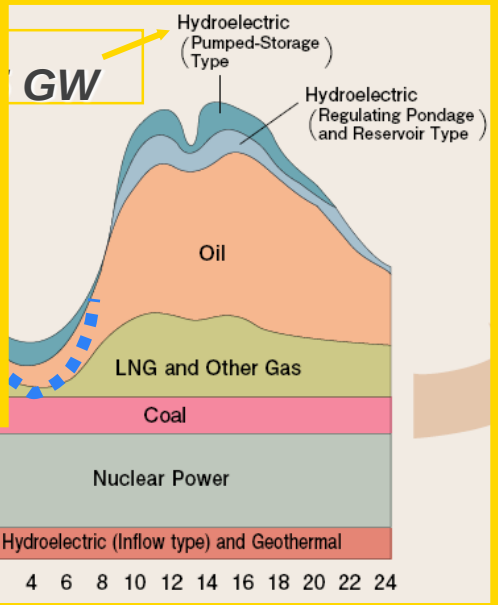


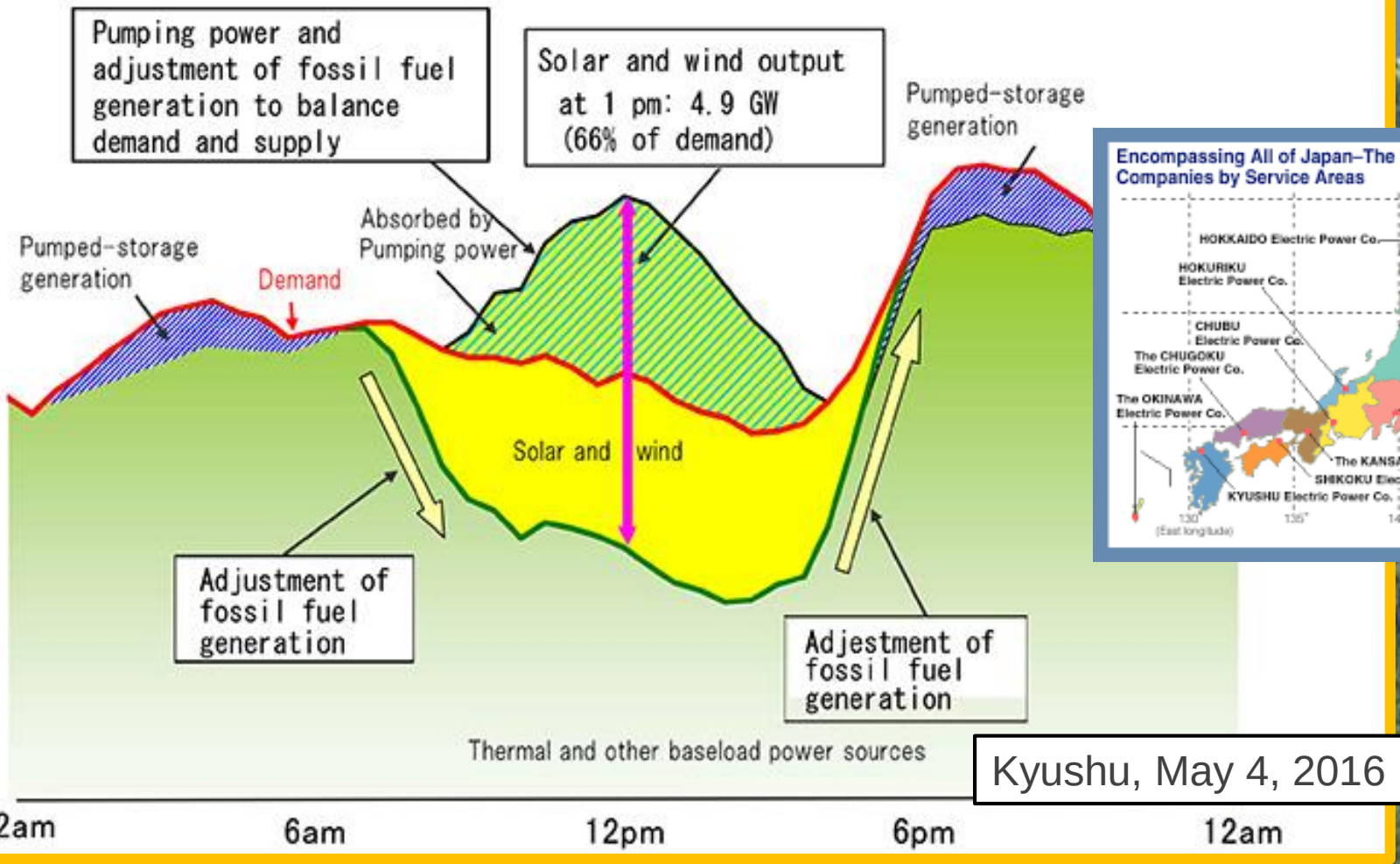
Japan's summer peak

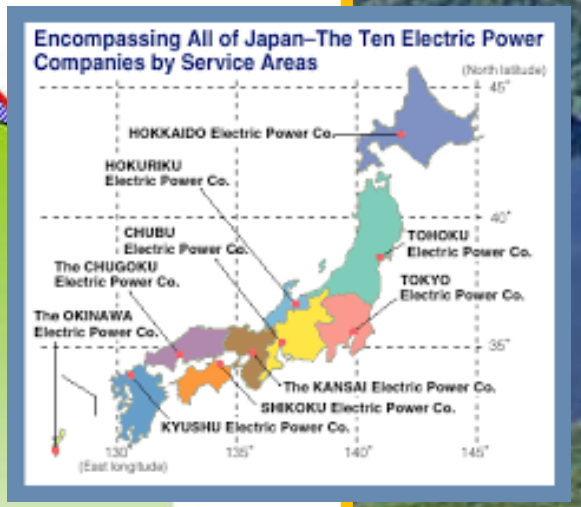





< Nuclear
Pumped Hydro >
Nuclear, GW
Pumped Hydro, GW
Japan
50
40
30
20
10
0
25
20
15
10
5
0
1970
1975
1980
1985
1990
1995
2000
2005
2010


GW
Hydroelectric (Pumped-Storage Type)
Hydroelectric (Regulating Pondage and Reservoir Type)
Oil
LNG and Other Gas
Coal
Nuclear Power
Hydroelectric (Inflow type) and Geothermal
Base Load Supply
0 2 4 6 8 10 12 14 16 18 20 22 24





Kyushu, May 4, 2016

ARENA PUMPED HYDRO ENERGY STORAGE (PHES)

$26.1M contributed → **14** studies → **$76.7M** value

Potential New Storage Capacity
>358 GWh

Potential New Pumping Capacity
3050 MW

Power for
915,000 homes

Development & Construction
4-5 years

Total Project Value
$5B

7.5 days of storage
Of All Current Wind/Solar Capacity

Current Operating PHES Sites

1. **Tumut 3**
   Pumping Capacity **600 MW**
   15 GWh
2. **Wivenhoe**
   Pumping Capacity **500 MW**
   5 GWh
3. **Shoalhaven Hydro Pump Storage Scheme**
   Pumping Capacity **240 MW**
   5 GWh

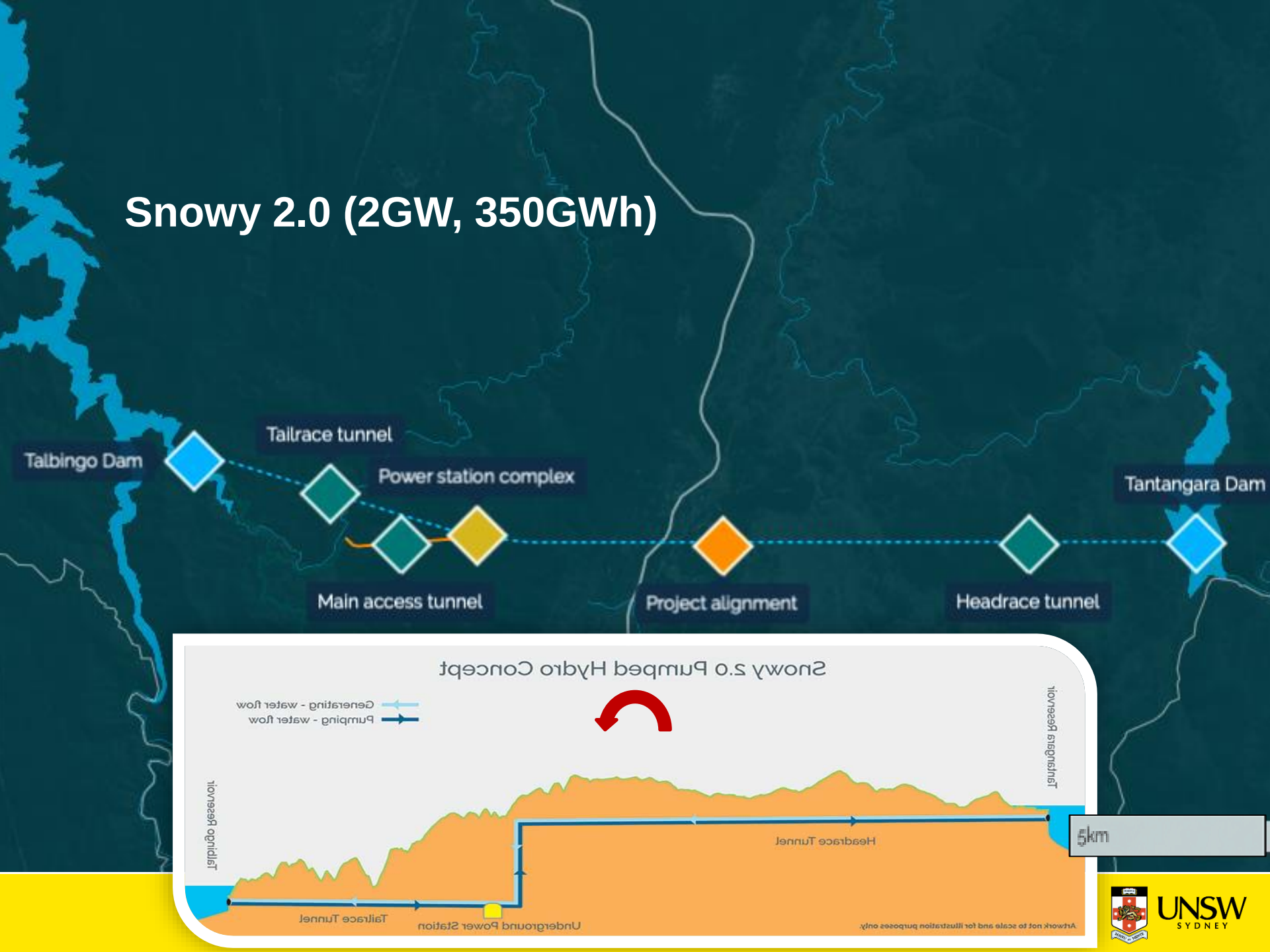
ARENA Funded Feasibility & Market Studies

4. **Cultana Pumped Hydro Project (2 studies)**
   Operator **Energy Australia**
   Pumping Capacity **225 MW**
   (Expected by 2021)
5. **Kidston (2 studies)**
   Operator **Genex Power Ltd**
   Pumping Capacity **250 MW**
   (Expected by 2021)
6. **Battery of the Nation**
   - Expanding Existing Hydro Sites (2 studies)
   - Future NEM (2 studies)
   - PHES study (2 studies)

   Operator **Hydro - Tasmania**
   Pumping Capacity
   Tarraleah : Additional 220MW
   Gordon : Additional 30MW
7. **Iron Duchess North**
   Operator **One Steel**
   Pumping Capacity **90 MW**
8. **Snowy 2.0**
   Operator **Snowy Hydro**
   Pumping Capacity **2000 MW**
9. **STORES Study**
   Operator **ANU**
   Pumping Capacity **N/A**
10. **Shoalhaven Hydro Pump Storage Expansion**
    Operator **Origin Energy**
    Pumping Capacity
    Additional 235 MW

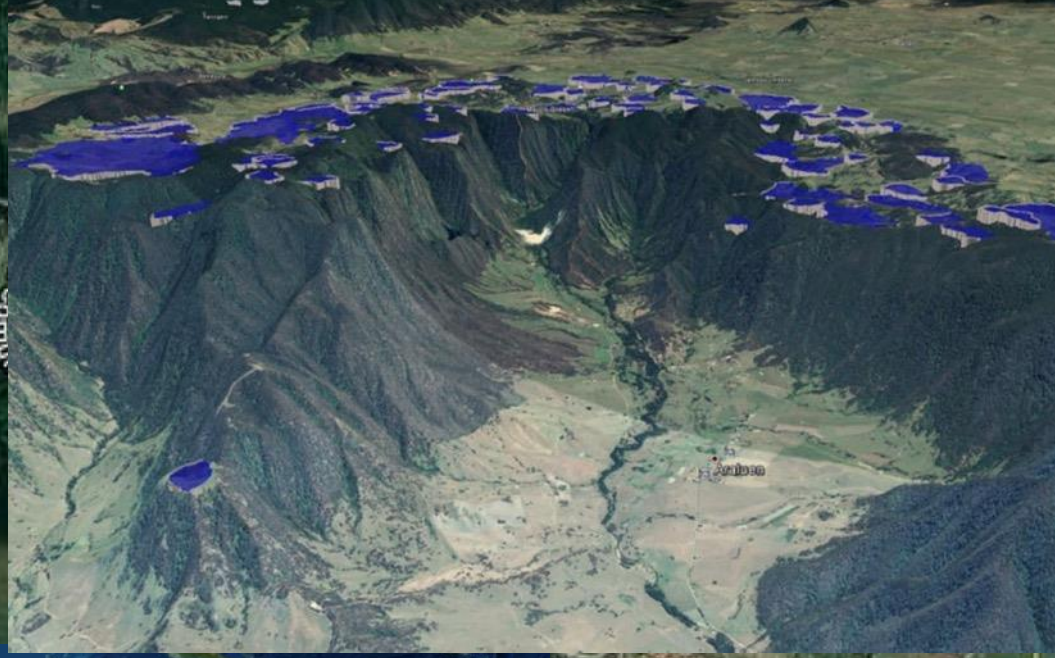
ARENA

Snowy 2.0 (2GW, 350GWh)

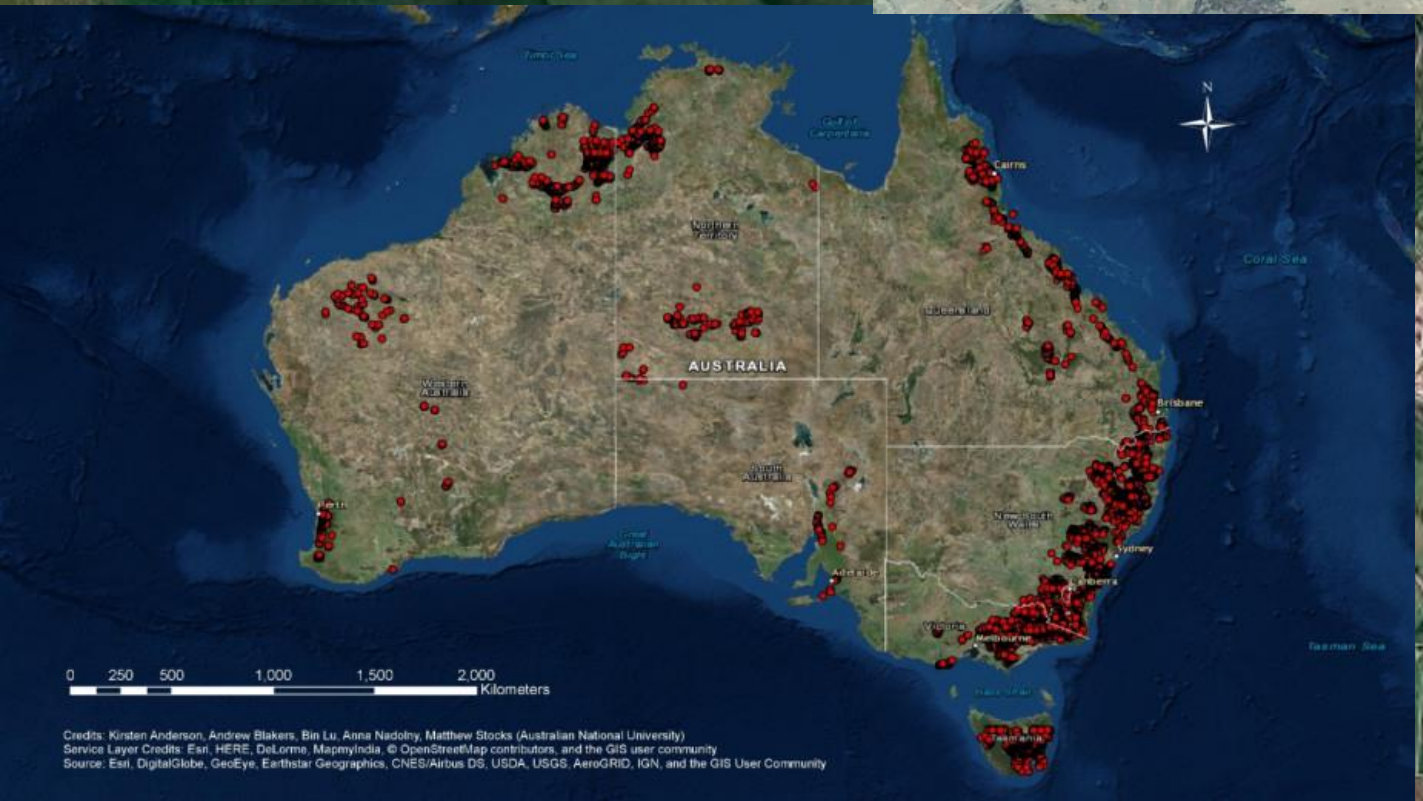


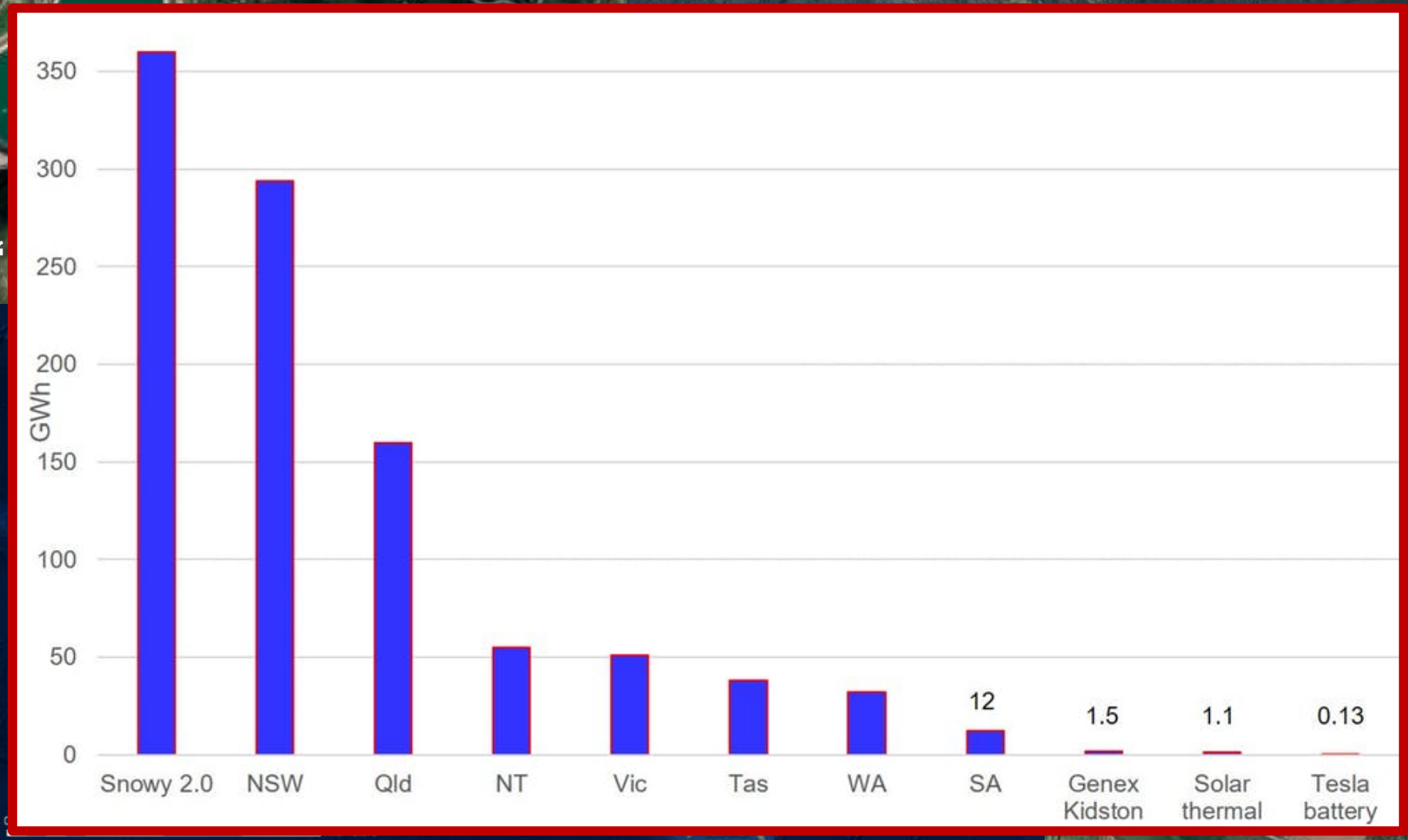
“Off river” pumped hydro

Presenzano (1GW, 5GWh)



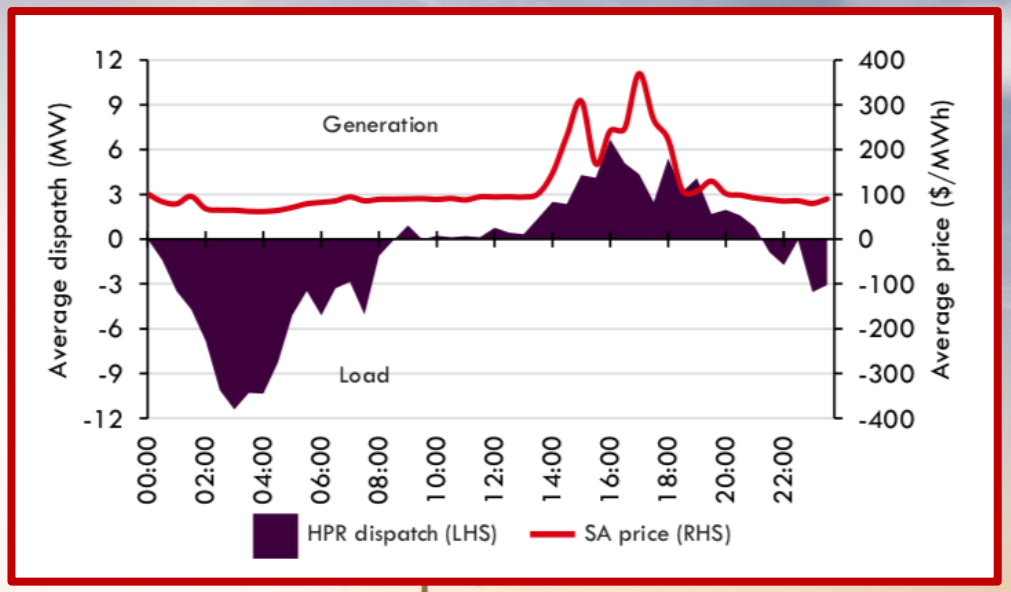
“Off river” pumped hydro



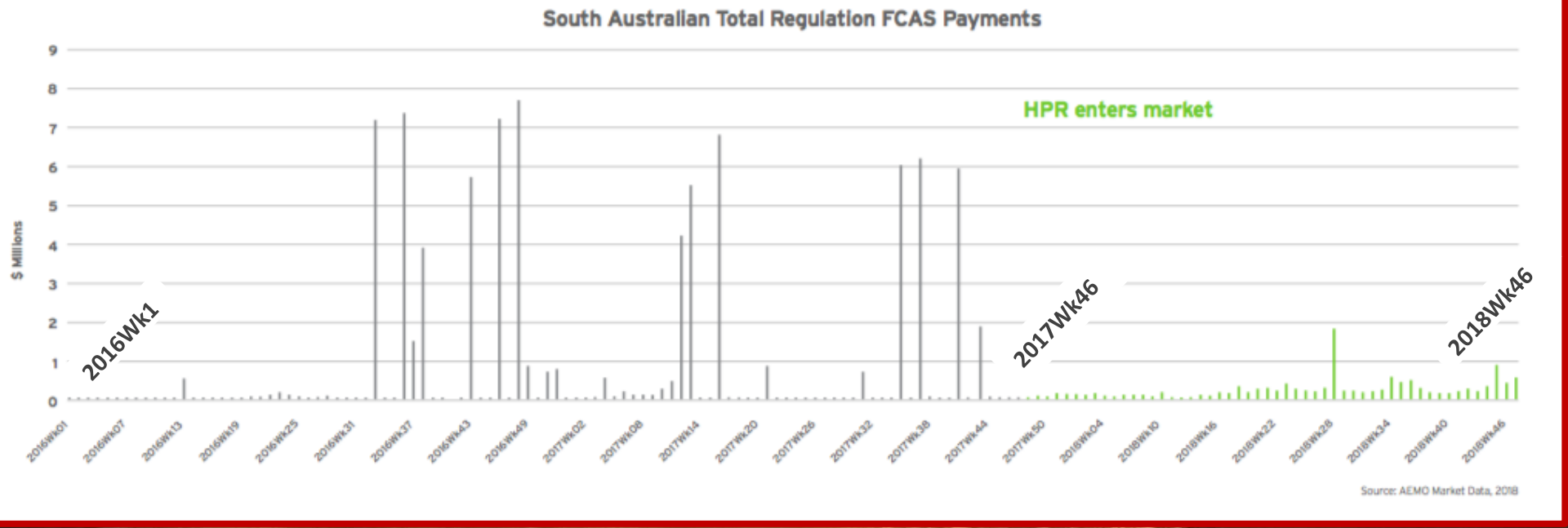


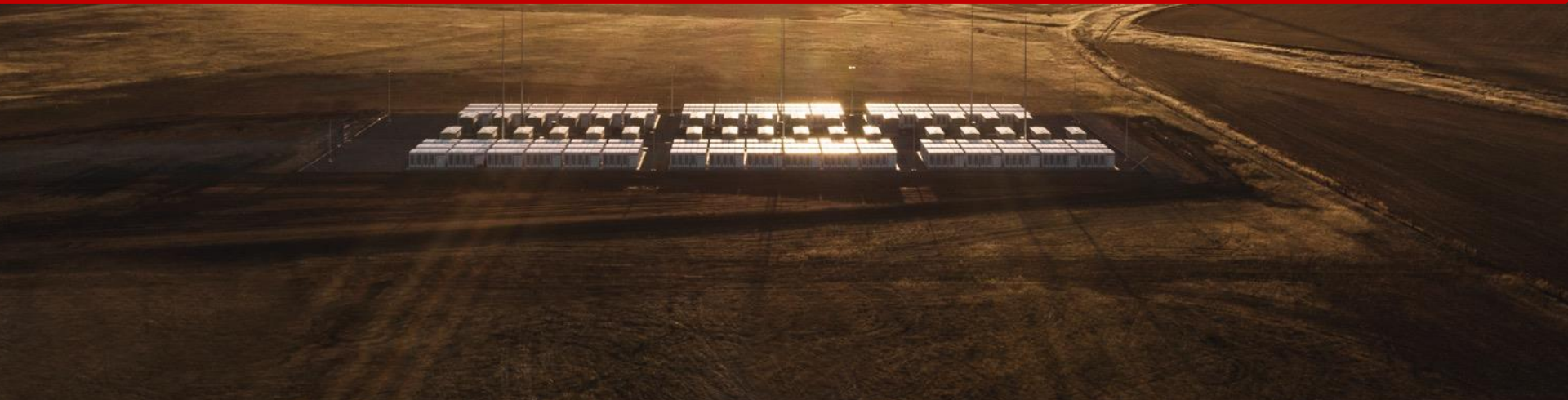
Tesla “Big Battery” Hornsdale (100MW, 129MWh)

Tesla “Big Battery” Hornsdale (100MW, 129MWh)



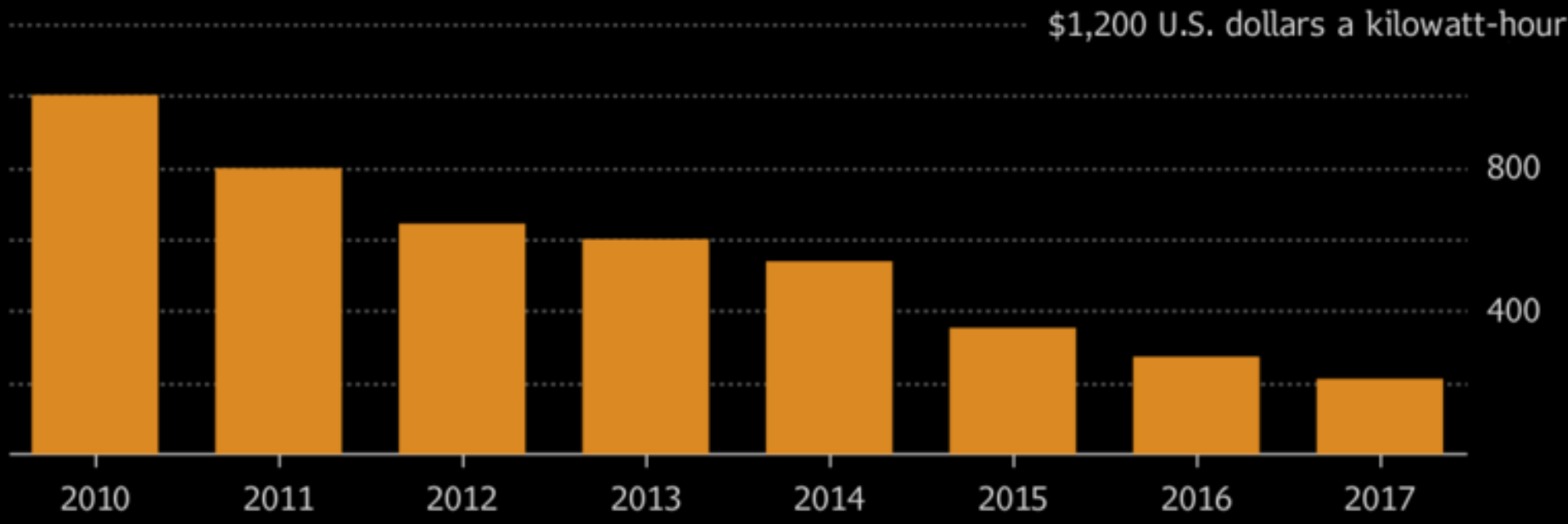
Tesla “Big Battery” Hornsdale (100MW, 129MWh)





Cheaper Batteries

Lithium-ion battery prices just keep falling. They're down 24% from 2016 levels.



Note: Figures are volume-weighted averages
Source: Bloomberg New Energy Finance survey of more than 50 companies

Bloomberg

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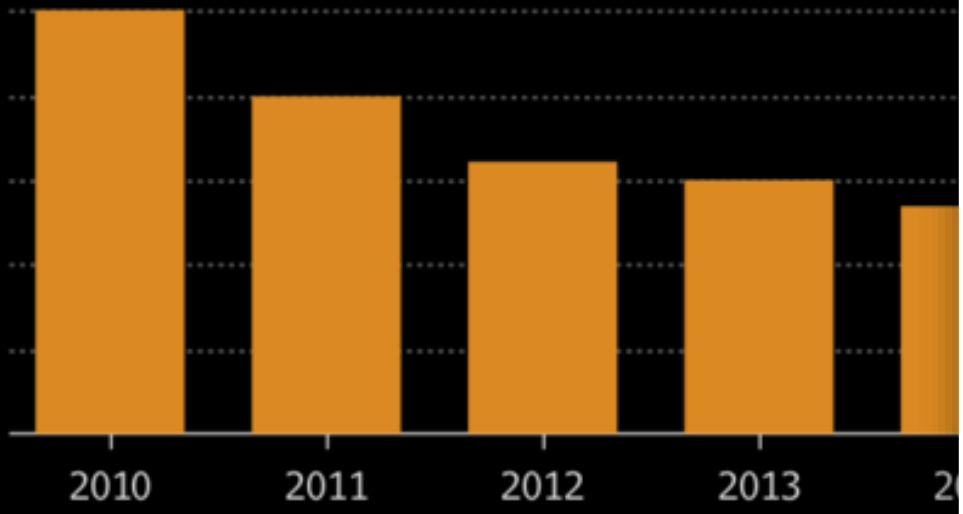

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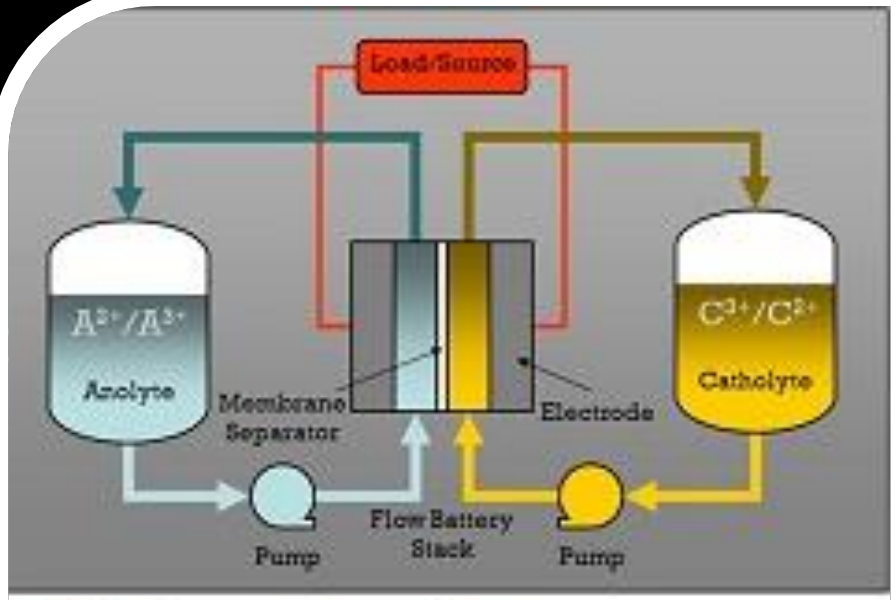

- **Discharge reaction**
  - $C^{3+} + e^- \rightarrow C^{2+}$ (reduction)
  - $A^{2+} \rightarrow A^{3+} + e^-$ (oxidation)
- **Charge reaction**
  - $C^{2+} \rightarrow C^{3+} + e^-$ (oxidation)
  - $A^{3+} + e^- \rightarrow A^{2+}$ (reduction)

Bloomberg

Cheaper Batteries

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A REDOX BATTERY FOR

REMOTE ENERGY STORAGE

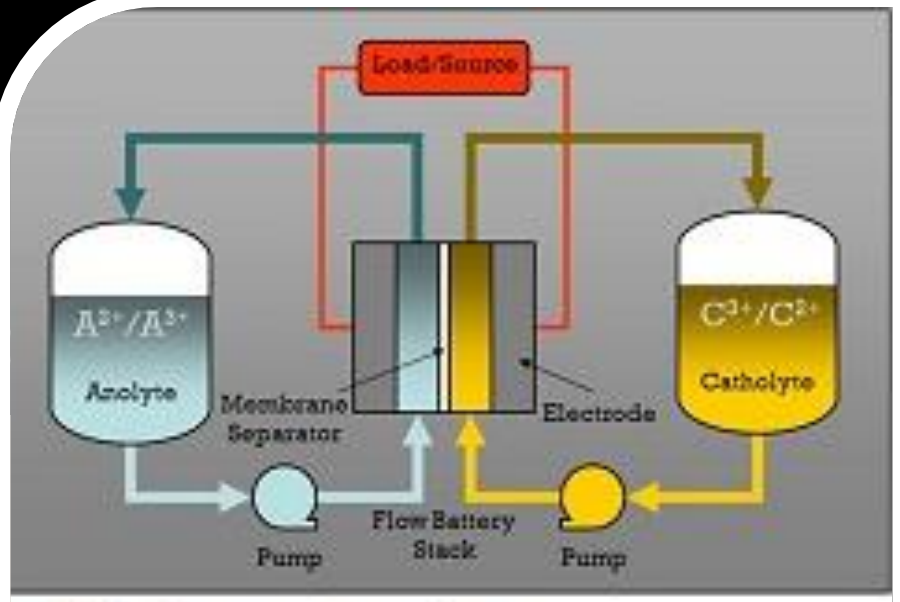
R. E. BRAND

Supervisor : Dr. M. A. Green

This thesis is submitted to the School of Electrical Engineering and Computer Science in partial fulfilment of the requirements for the degree of Bachelor of Engineering.

University of New South Wales

November, 1982



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0 companies

Bloomberg

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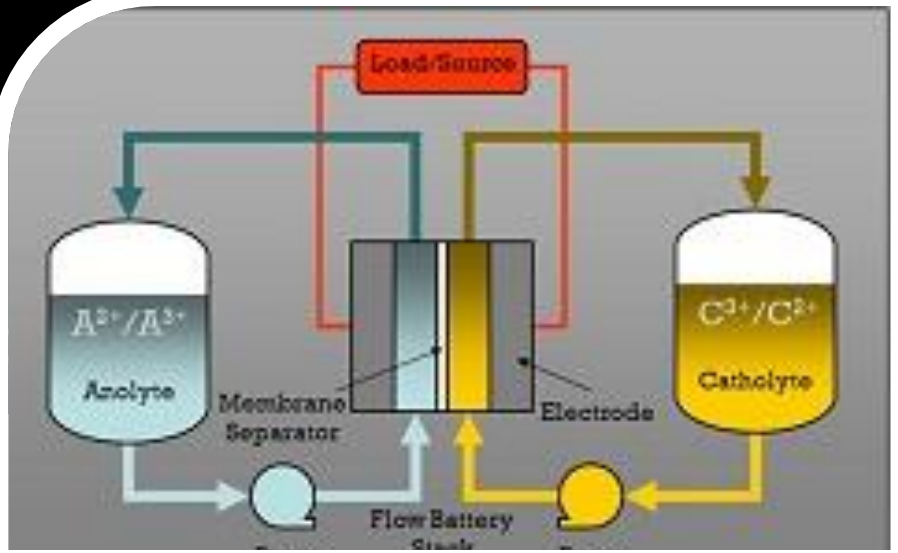

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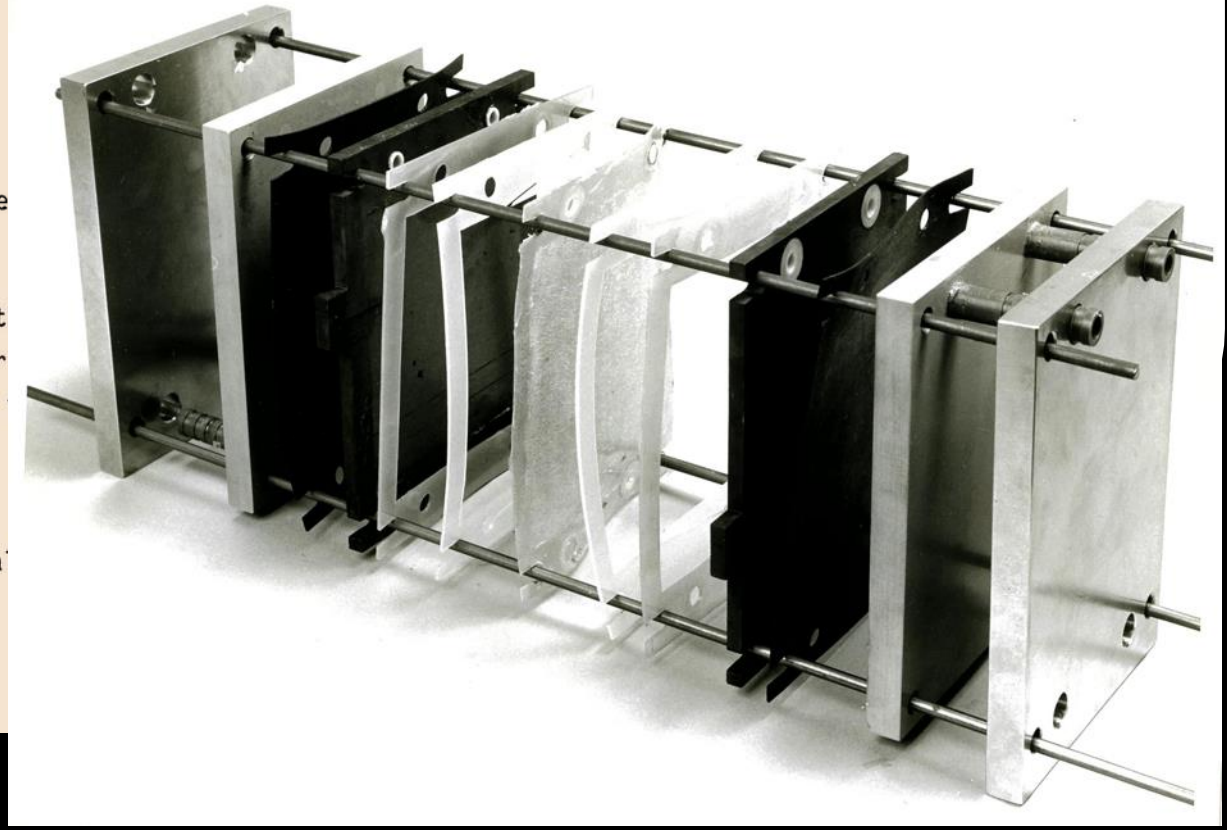

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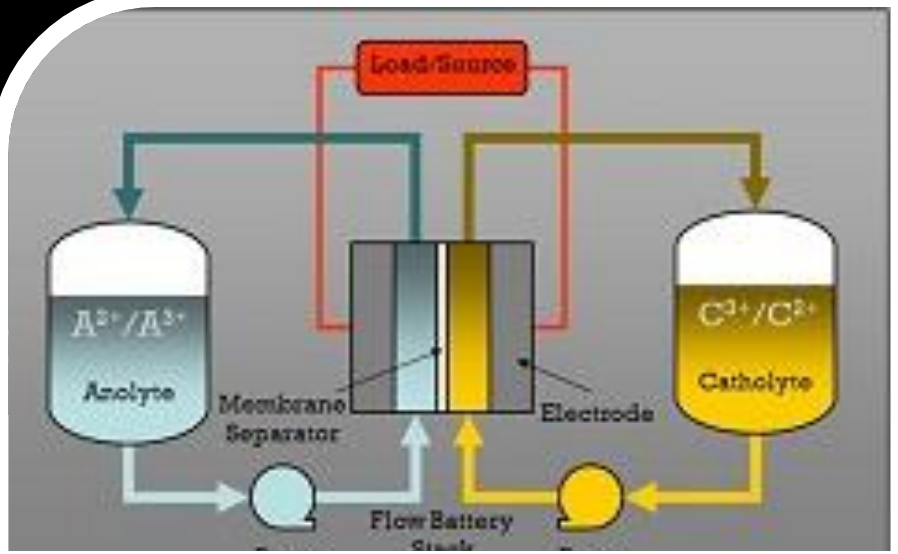

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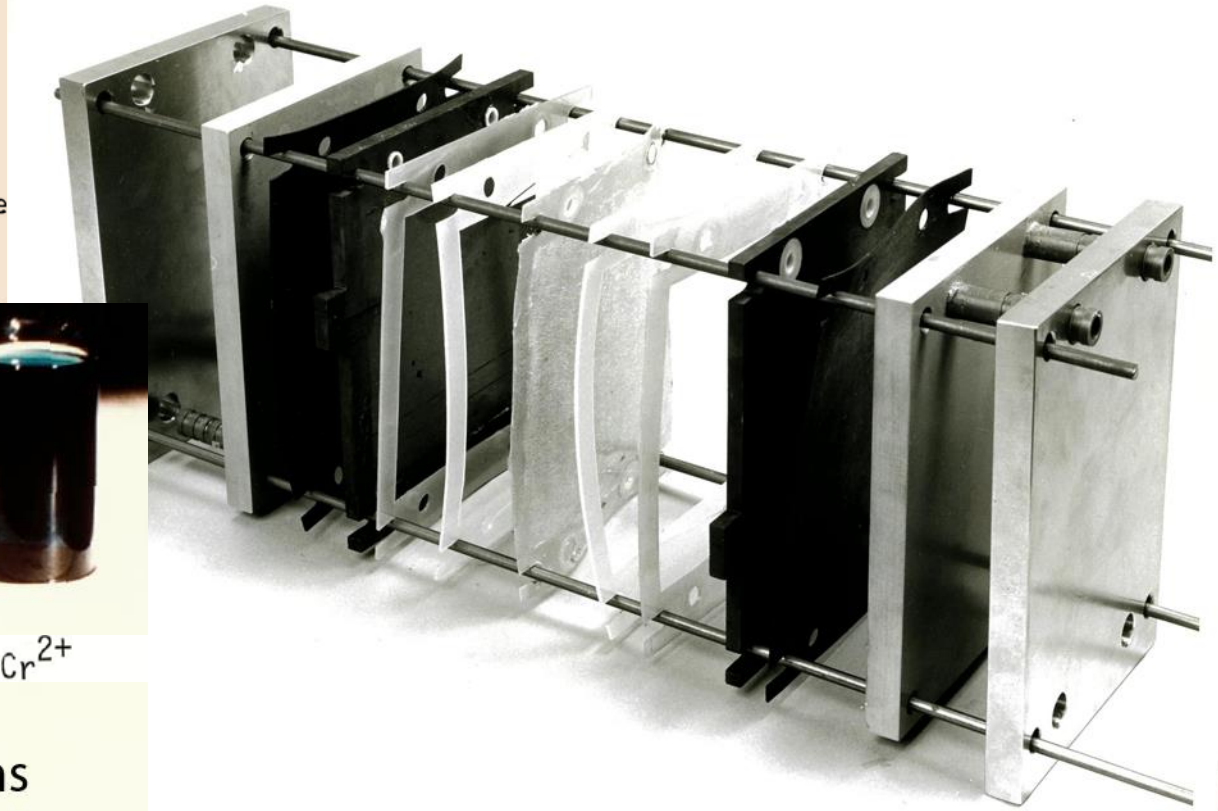

Colours of Redox Solutions

Cheaper Batteries

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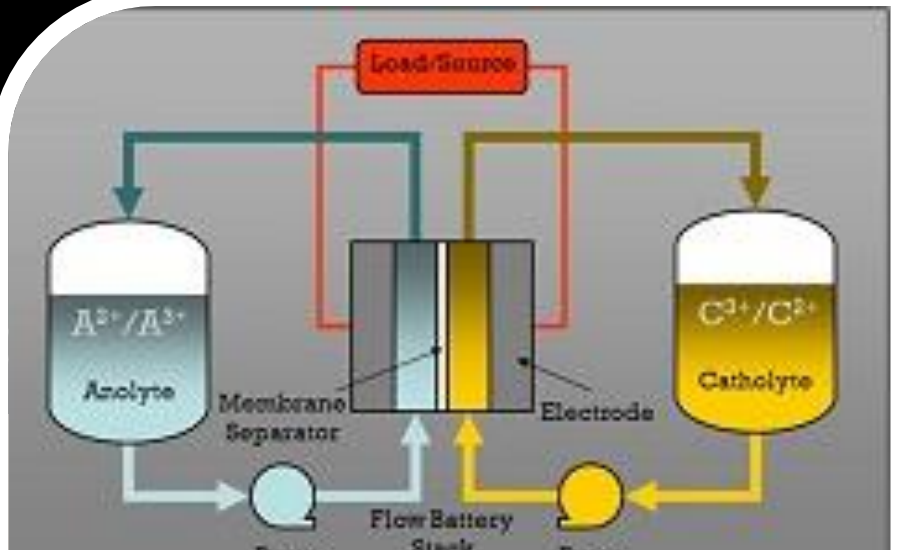

A REDOX BATTERY FOR

REMOTE ENERGY STORAGE

JOURNAL OF THE ELECTROCHEMICAL SOCIETY

ACCELERATED

—BRIEF COMMUNICATIONS—

MAY

1986

New All-Vanadium Redox Flow Cell

M. Skyllas-Kazacos,* M. Rychcik, R. G. Robins, and A. G. Fane

School of Chemical Engineering and Industrial Chemistry, University of New South Wales, Kensington, New South Wales 2033, Australia

M. A. Green

School of Electrical Engineering and Computer Sciences, University of New South Wales, Kensington, New South Wales 2033, Australia

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kilowatt-hour

800

400

017

Bloomberg

Cheaper Batteries

Lithium-ion battery prices just

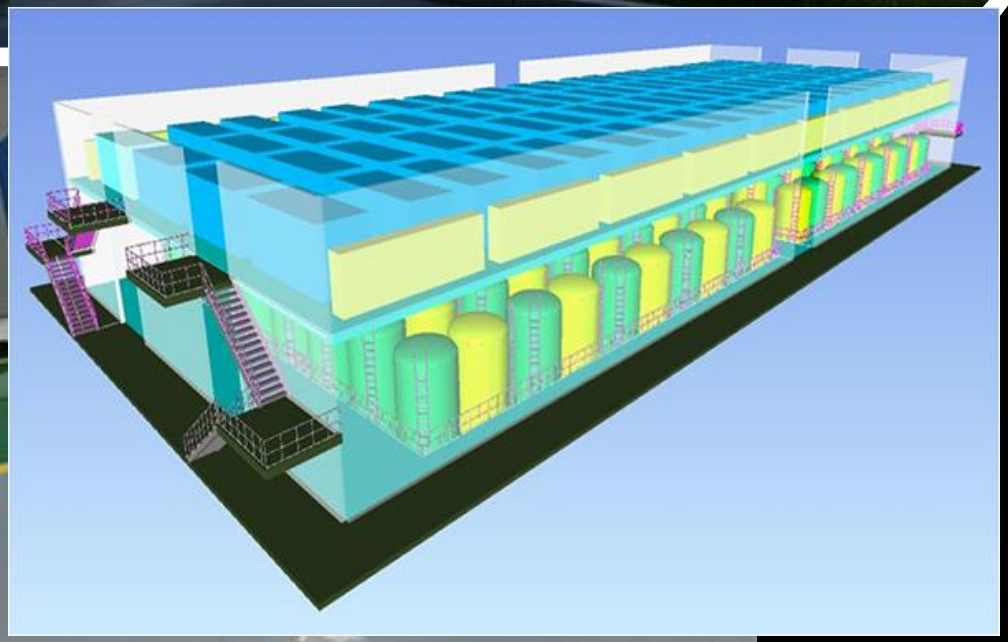
017

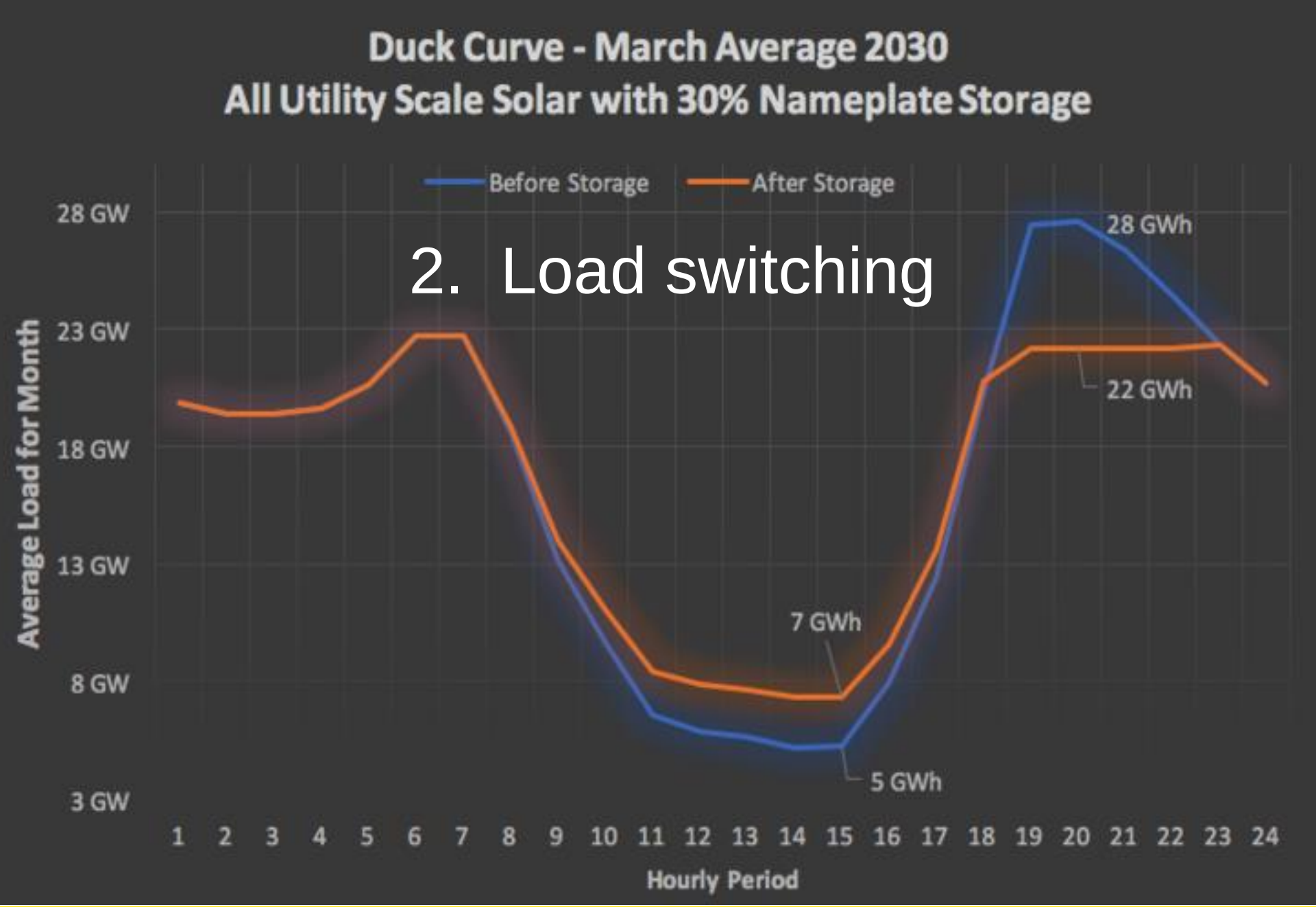
Bloomberg

Cheaper Batteries

Lithium-ion battery prices just

Vanadium Redox Flow (200MW, 800MWh)

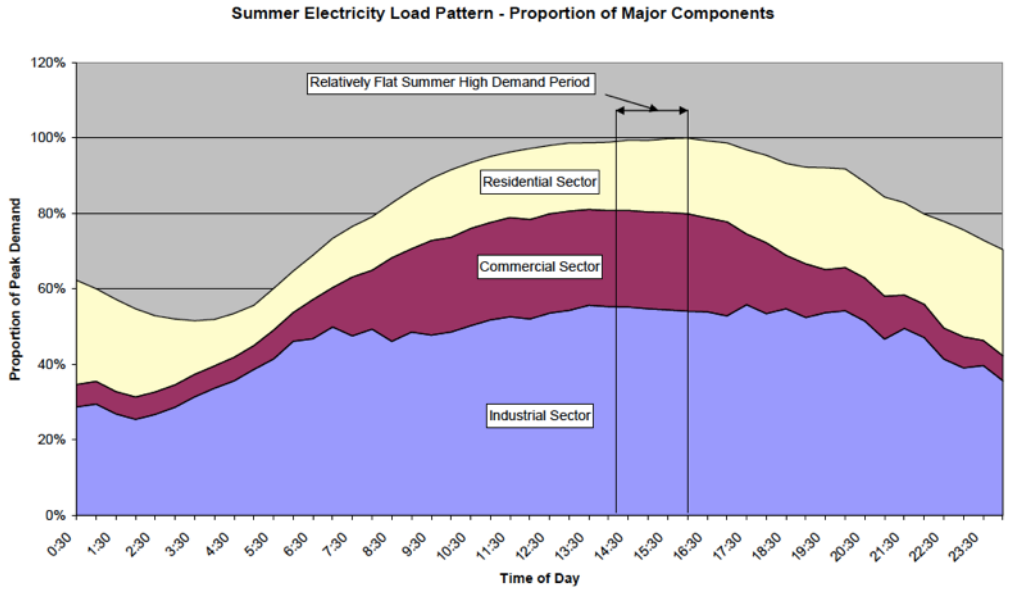




2. Load switching

UNSW SYDNEY

Load switching: Boost daytime not night demand



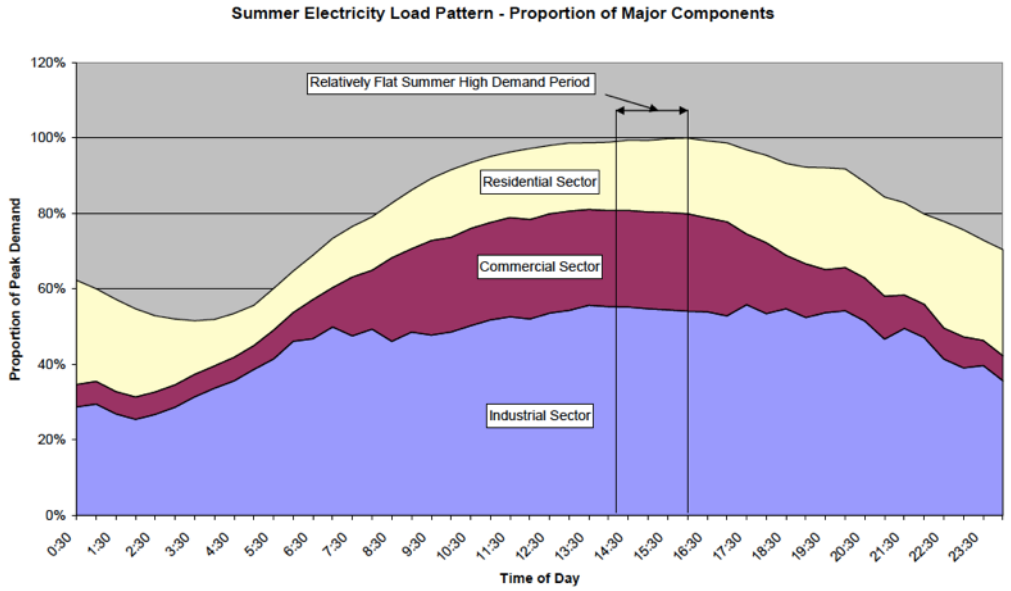
EMET
ENGINEERING & MANAGEMENT CONSULTANTS

Day of NSW peak demand in 2003 Summer

UNSW SYDNEY

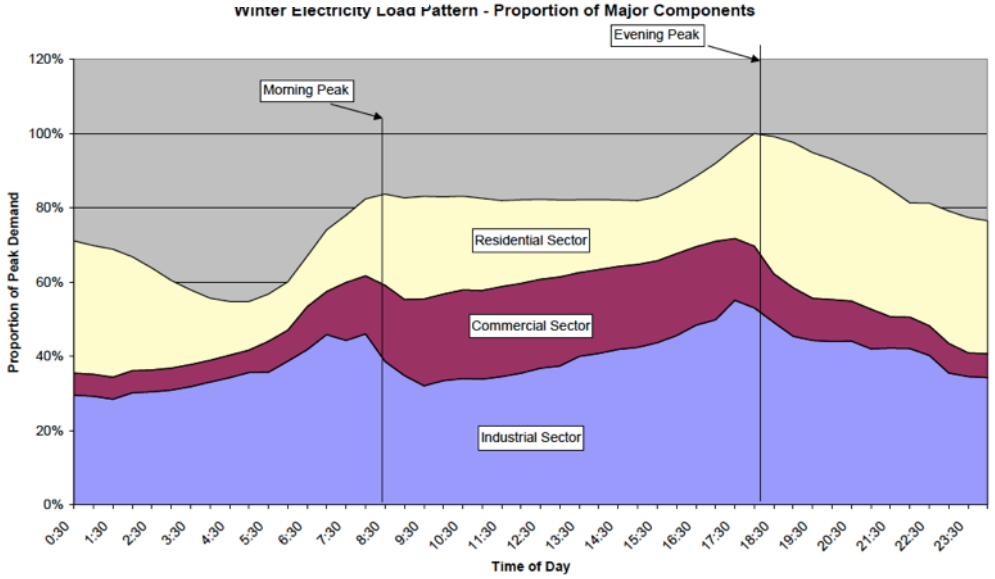
Load switching: Boost daytime not night demand

2004

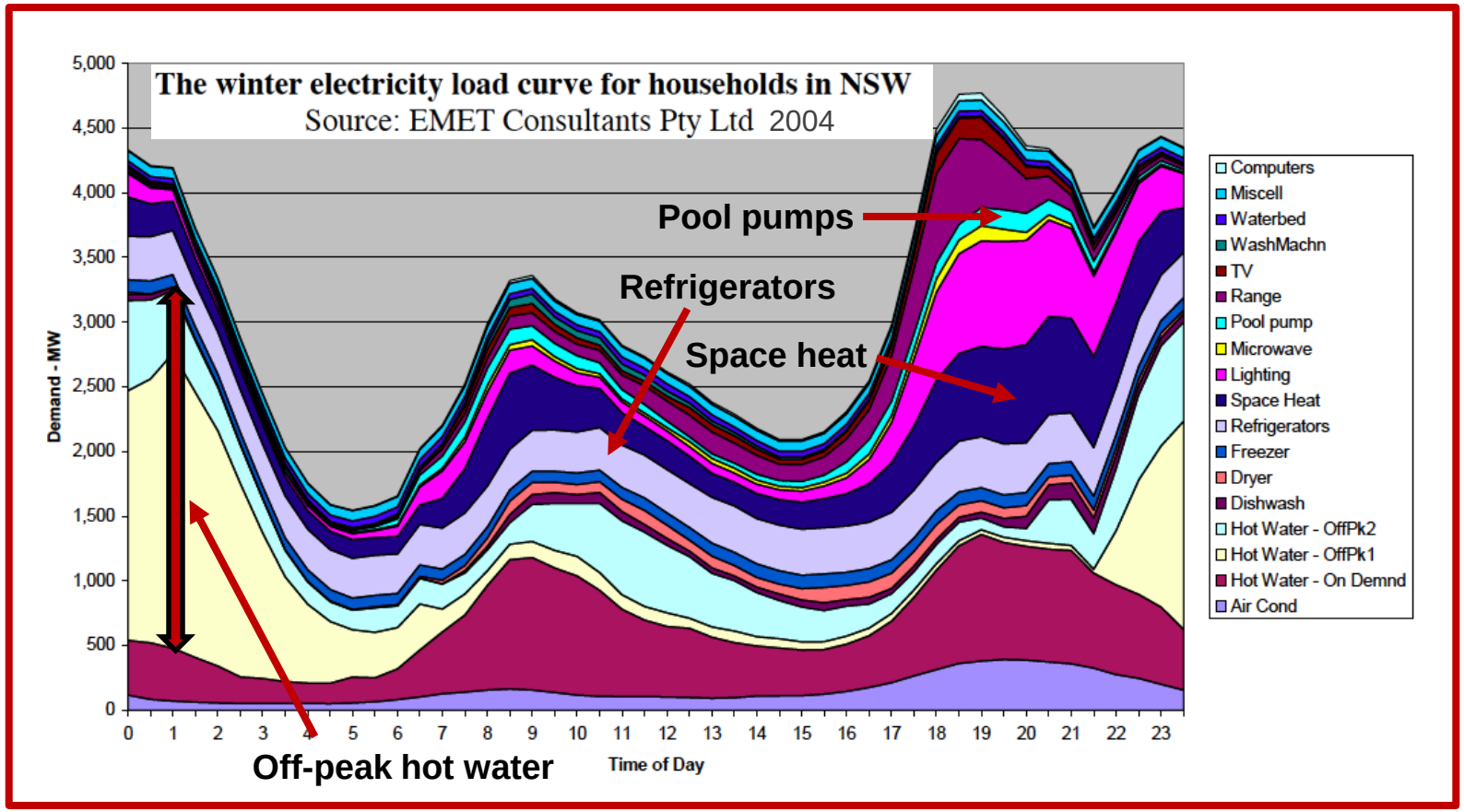


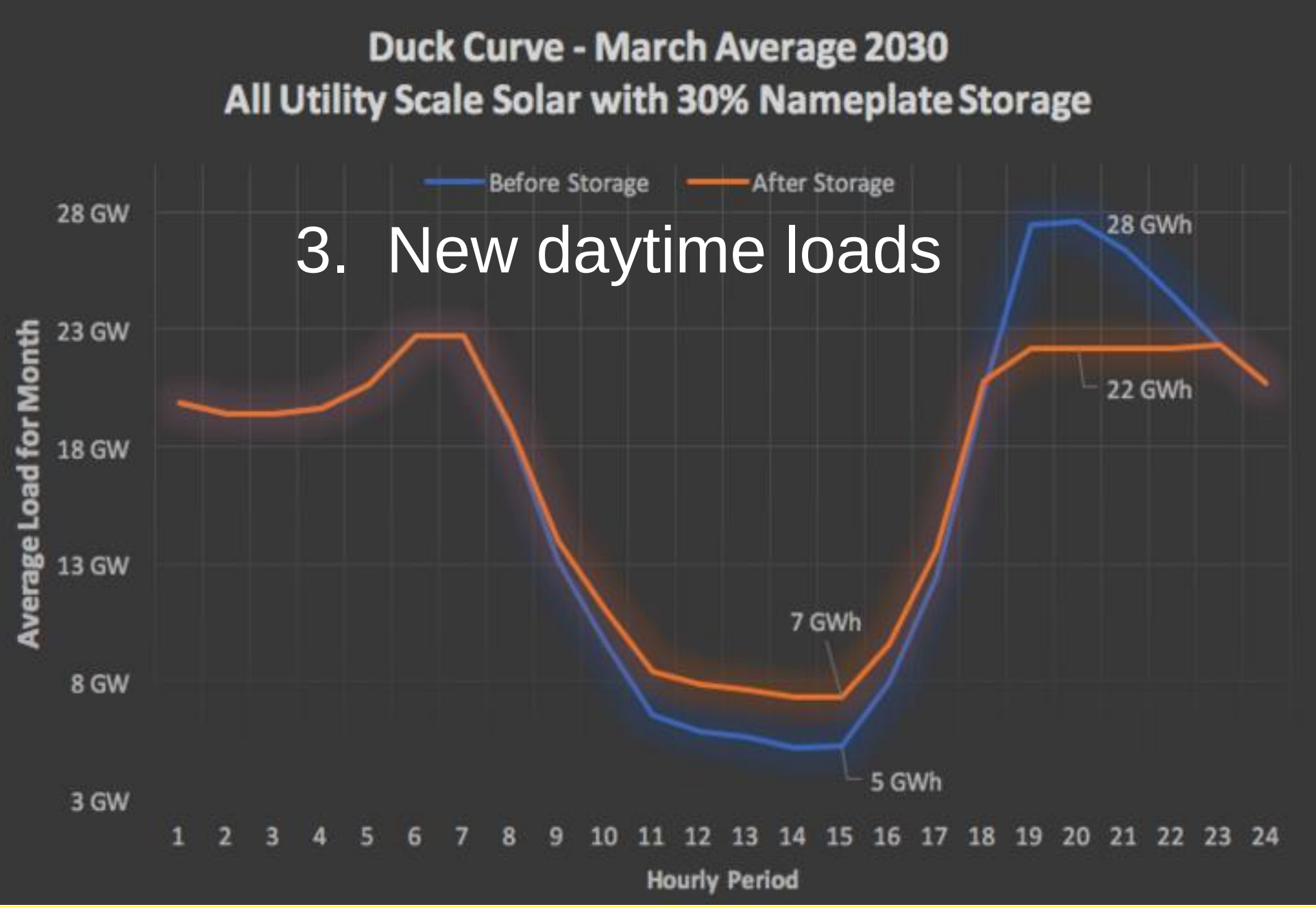
Day of NSW peak demand in 2003 Summer

Day of peak demand in 2002 Winter



Load switching: Boost daytime not night demand





3. New daytime loads

UNSW SYDNEY

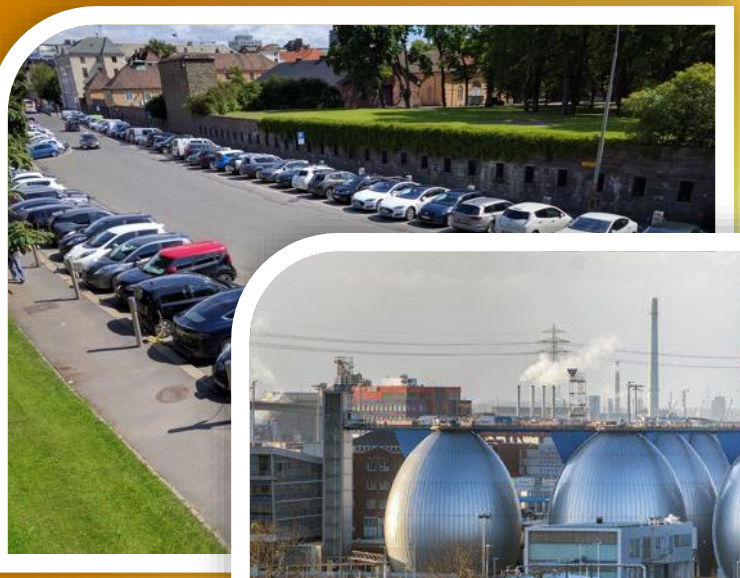
New night-time loads

New night-time loads

New daytime loads

1. Electric vehicle charging

New daytime loads



1. Electri

2. Desalination

New daytime loads

1. Electri

2. Desalir

3. Hydrogen from H_2O (other fuels)

New daytime loads

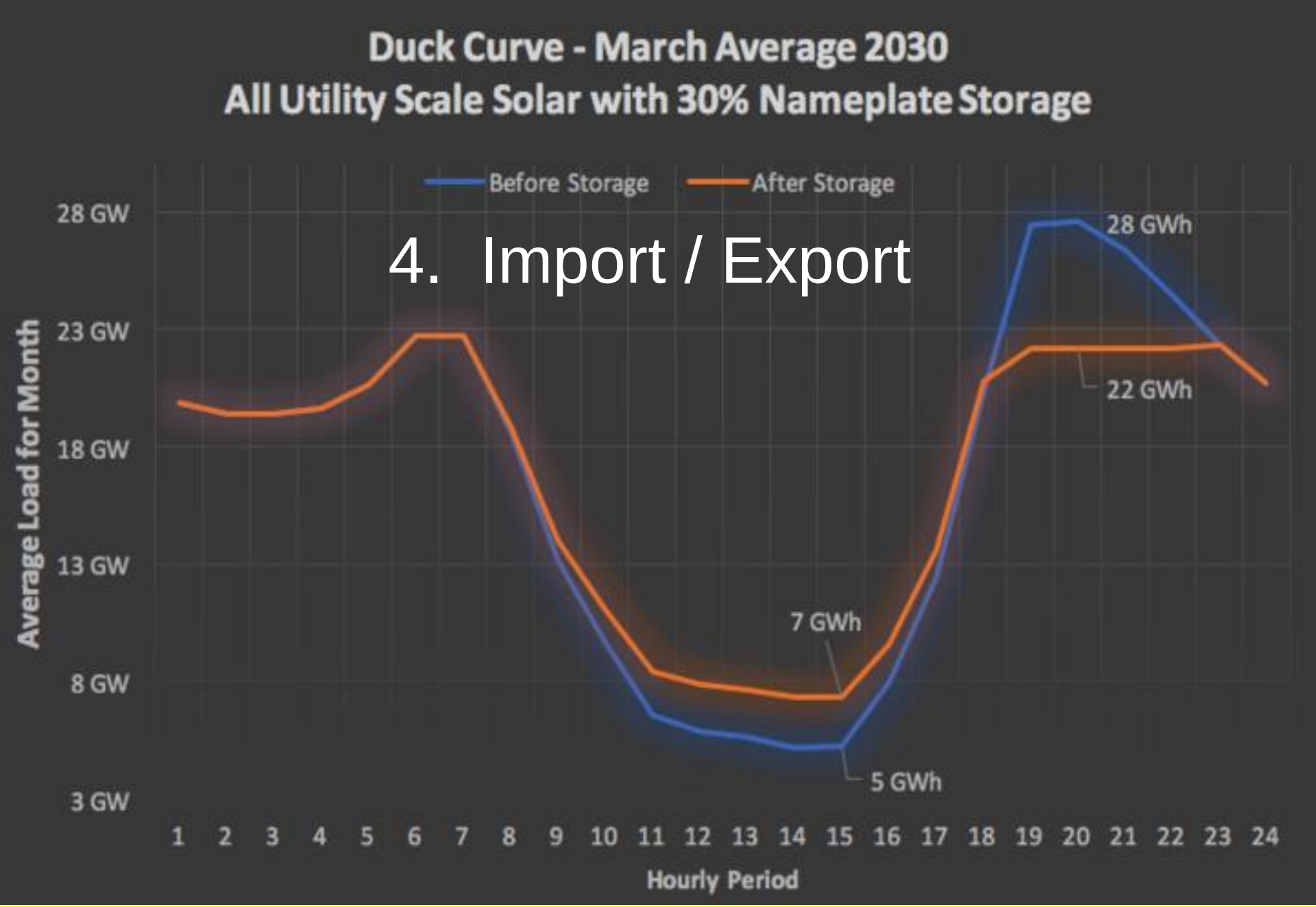
1. Electri

2. Desalir

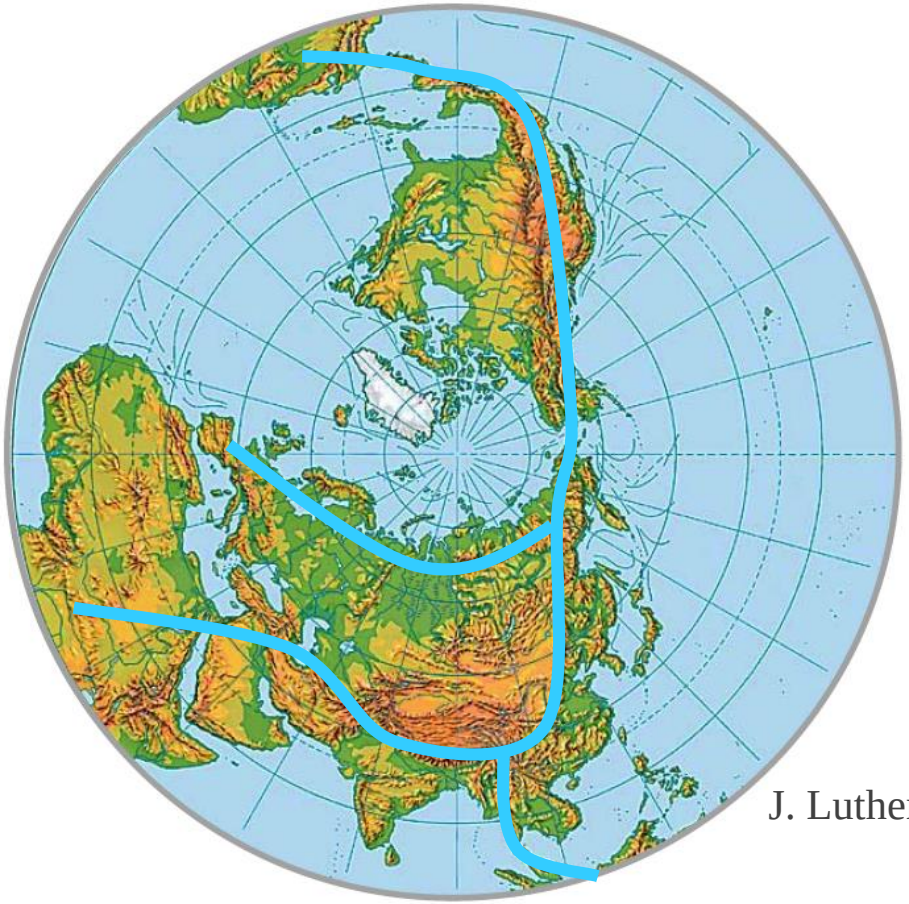
3. Hydrogen fror

4. CO2 removal, mineralisation

4. Import / Export



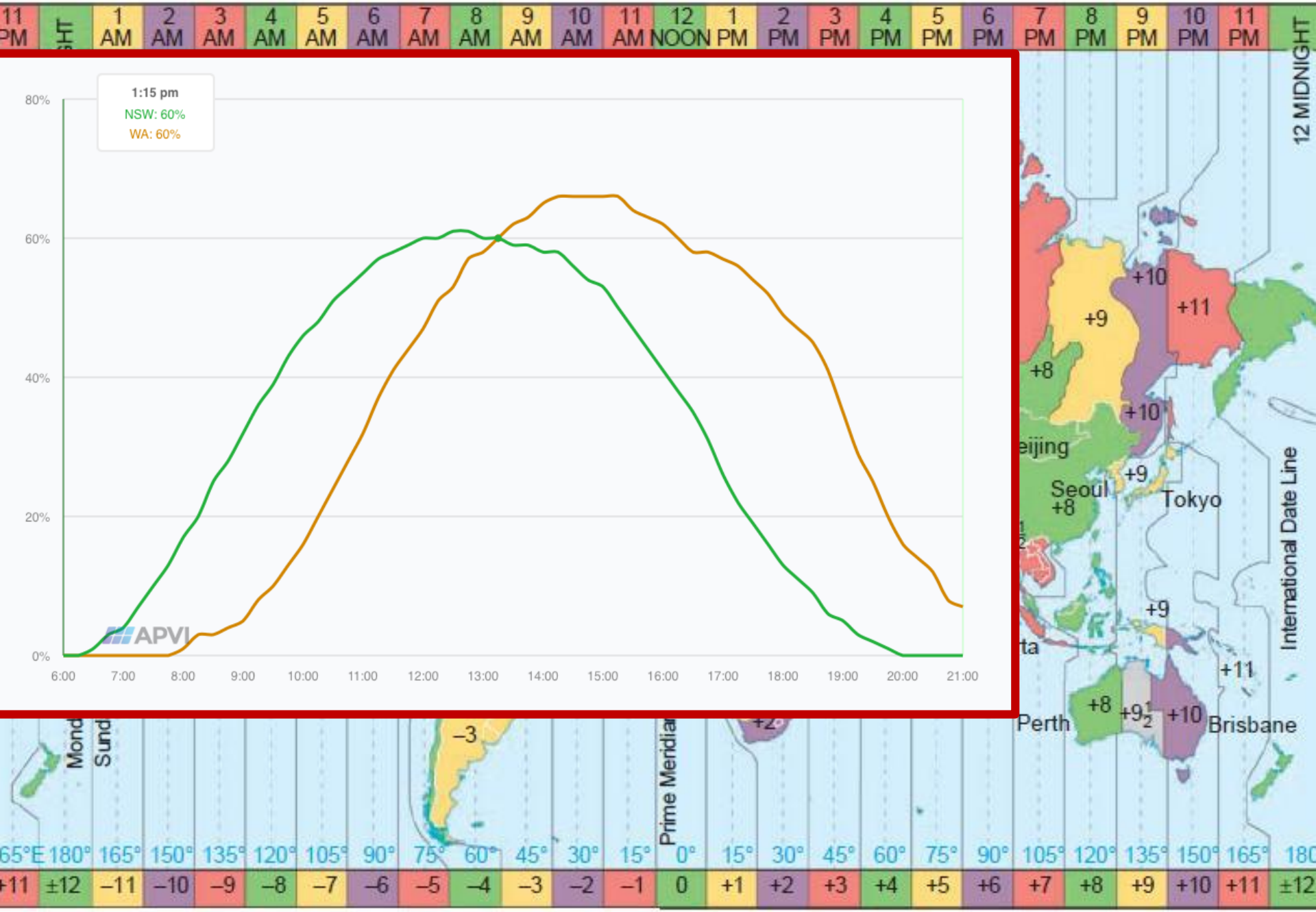
Sun always shining somewhere



J. Luther

Storage or immediate transmission?

1.16 Time zones of the world



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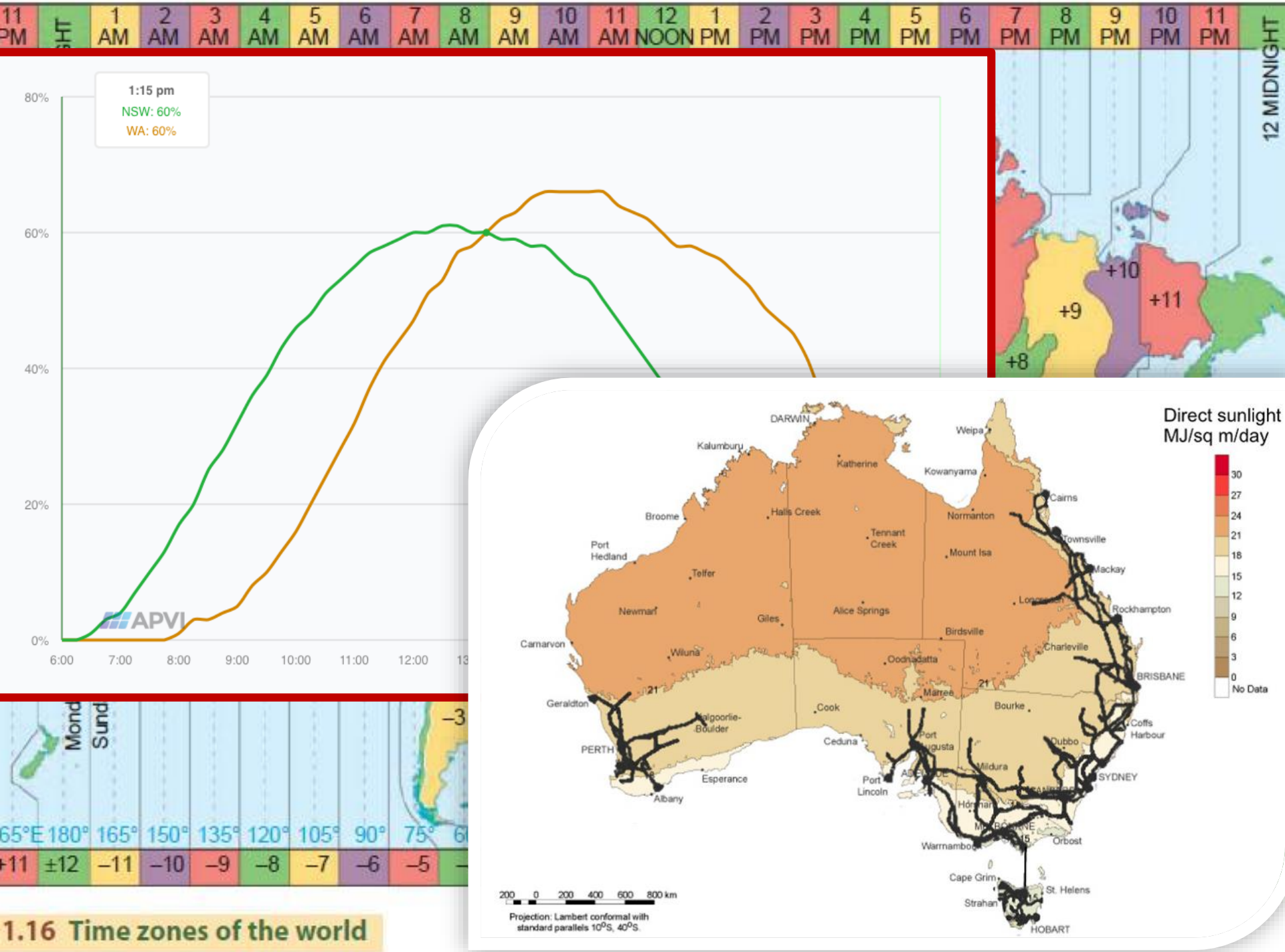
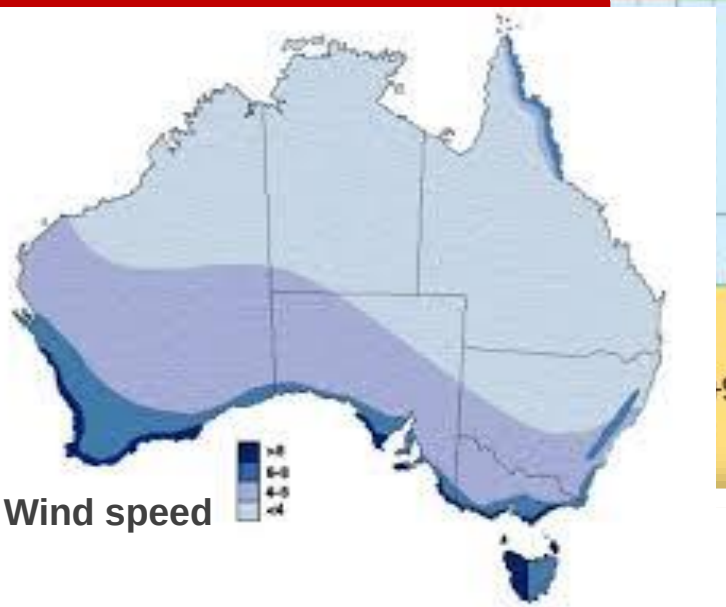
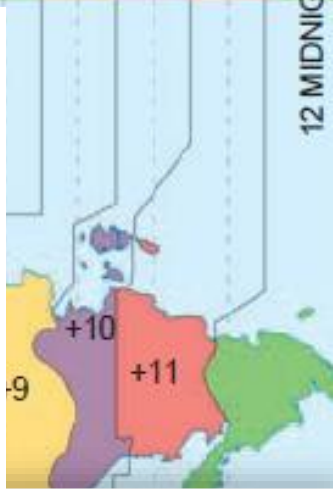
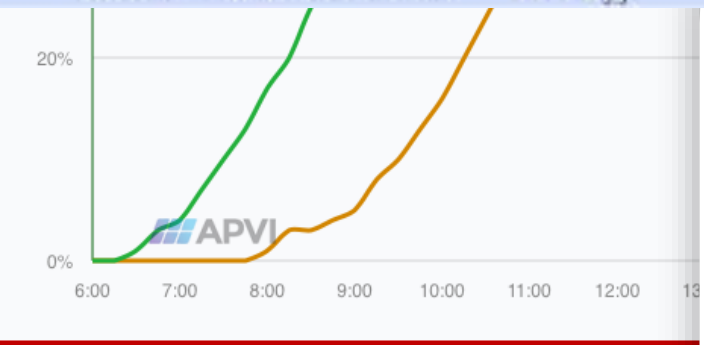
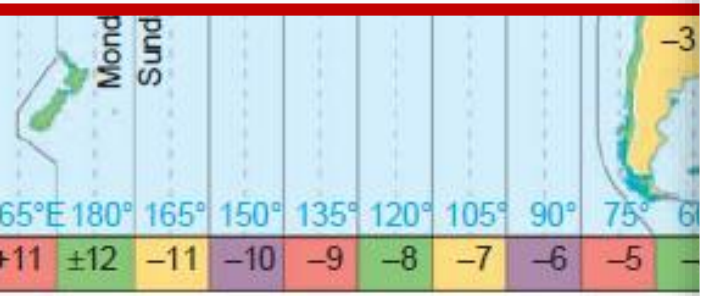

11 PM
1 AM
2 AM
3 AM
4 AM
5 AM
6 AM
7 AM
8 AM
9 AM
10 AM
11 AM
12 NOON
1 PM
2 PM
3 PM
4 PM
5 PM
6 PM
7 PM
8 PM
9 PM
10 PM
11 PM
12 MIDNIGHT
1:15 pm
NSW: 60%
WA: 60%
80%
60%
40%
20%
0%
6:00
7:00
8:00
9:00
10:00
11:00
12:00
APVI
+8
+9
+10
+11
Direct sunlight
MJ/sq m/day
30
27
24
21
18
15
12
9
6
3
0
No Data
DARWIN
Kalumburu
Weipa
Katherine
Kowanyama
Cairns
Broome
Halls Creek
Normanton
Tennant Creek
Townsville
Port Hedland
Mount Isa
Telfer
Mackay
Newman
Giles
Alice Springs
Rockhampton
Birdsville
Carnarvon
Charleville
Wiluna
Oodnadatta
BRISBANE
Marree
Geraldton
Cook
Bourke
Coffs Harbour
Kalgoorlie-Boulder
Ceduna
Dubbo
PERTH
Port Augusta
Mildura
SYDNEY
Esperance
Port Lincoln
Albany
Warrnambool
Orbost
Cape Grim
St. Helens
Strahan
HOBART
200 0 200 400 600 800 km
Projection: Lambert conformal with standard parallels 10°S, 40°S.
Mond
Sund
65°E
180°
165°
150°
135°
120°
105°
90°
75°
+11
±12
–11
–10
–9
–8
–7
–6
–5
1.16 Time zones of the world

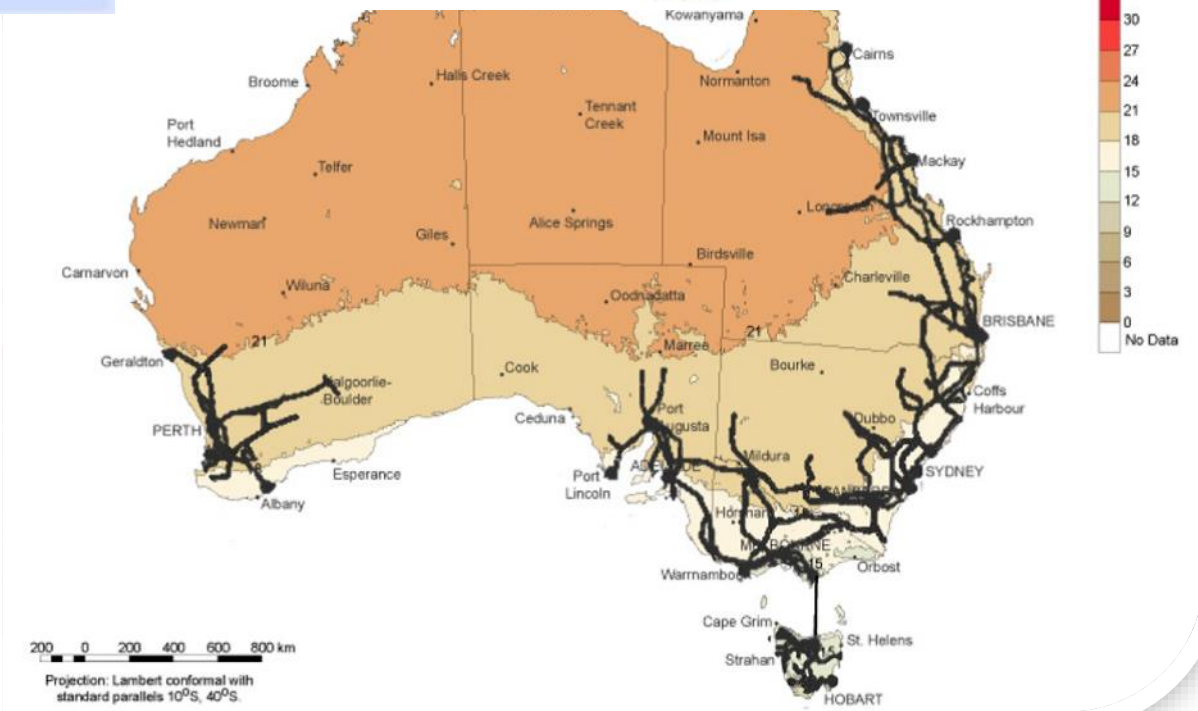
11 PM | 1 AM | 2 AM | 3 AM | 4 AM | 5 AM | 6 AM | 7 AM | 8 AM | 9 AM | 10 AM | 11 AM | 12 NOON | 1 PM | 2 PM | 3 PM | 4 PM | 5 PM | 6 PM | 7 PM | 8 PM | 9 PM | 10 PM | 11 PM











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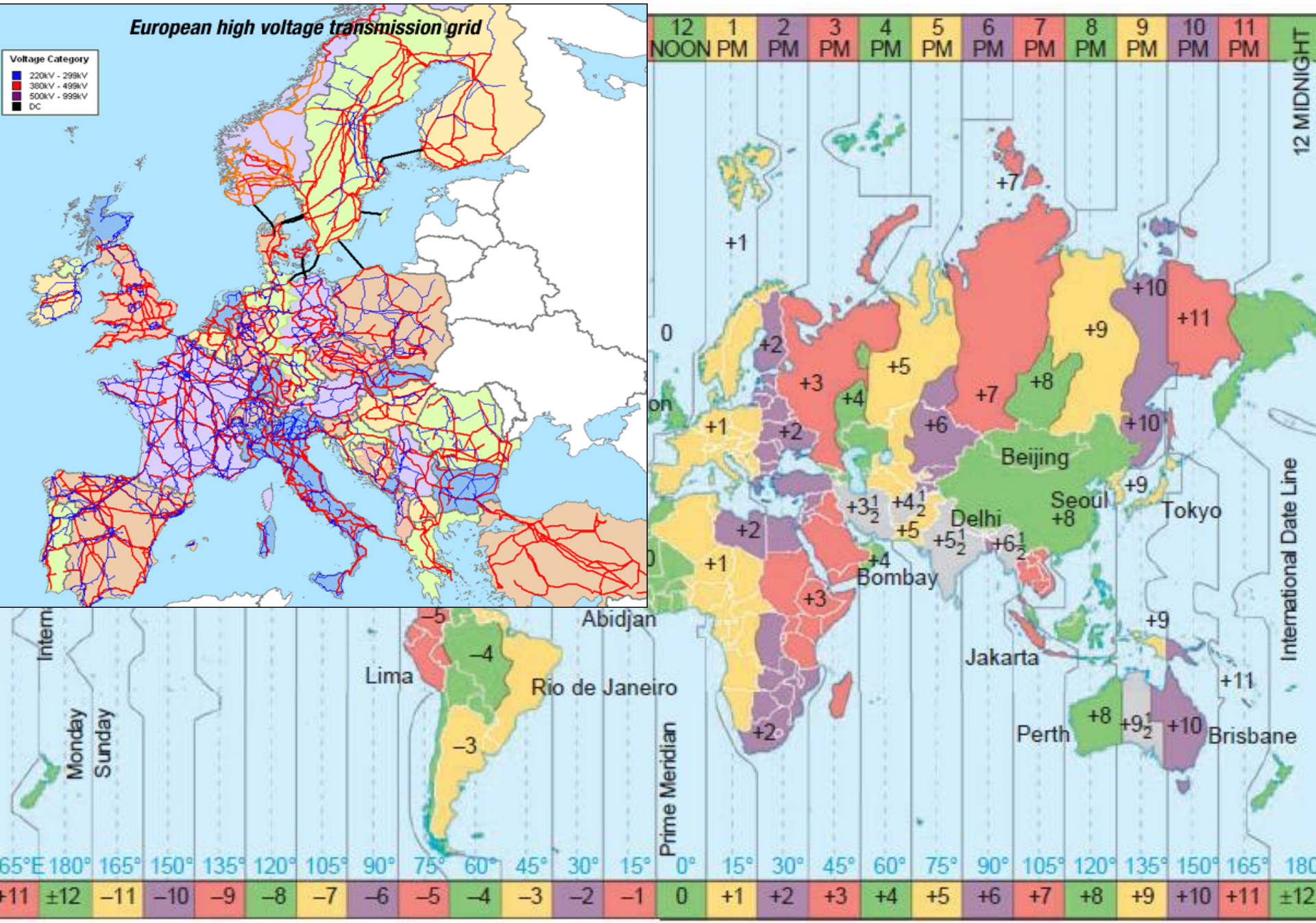

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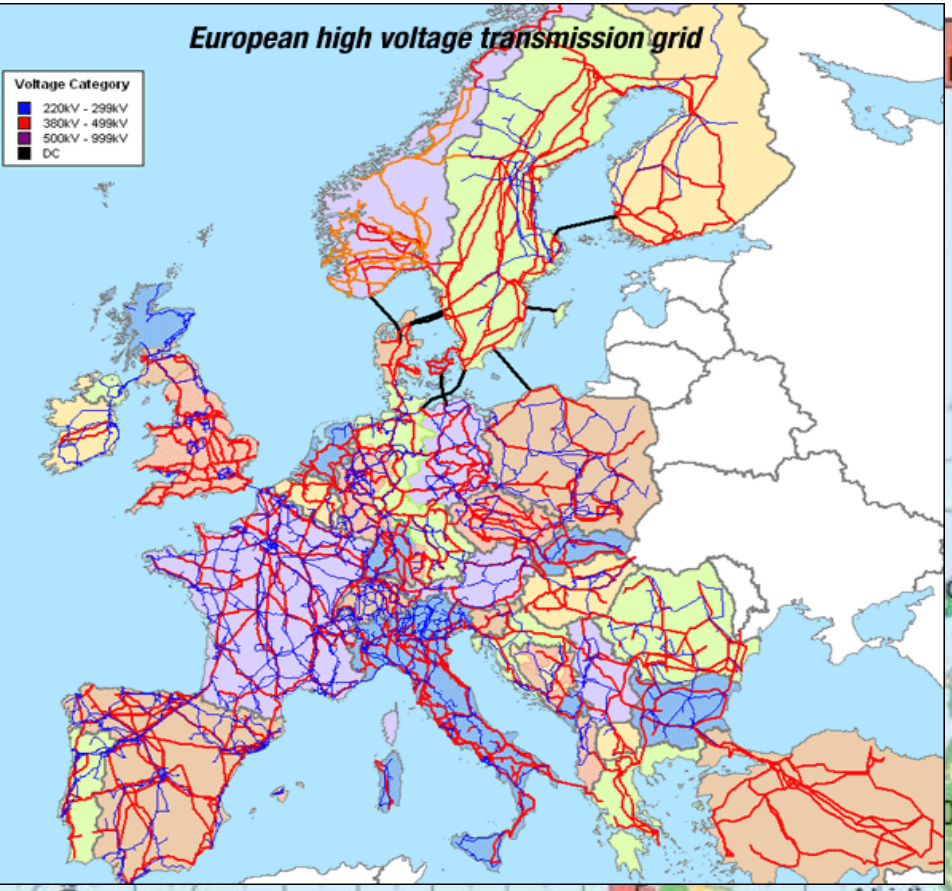
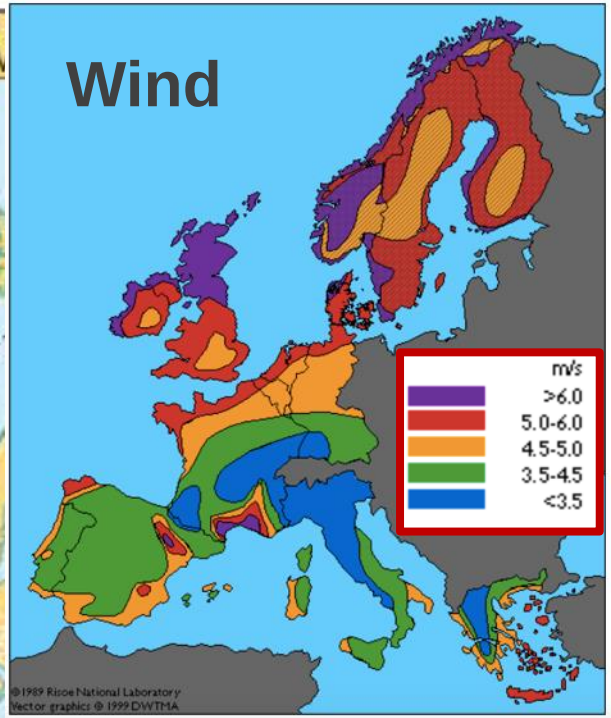
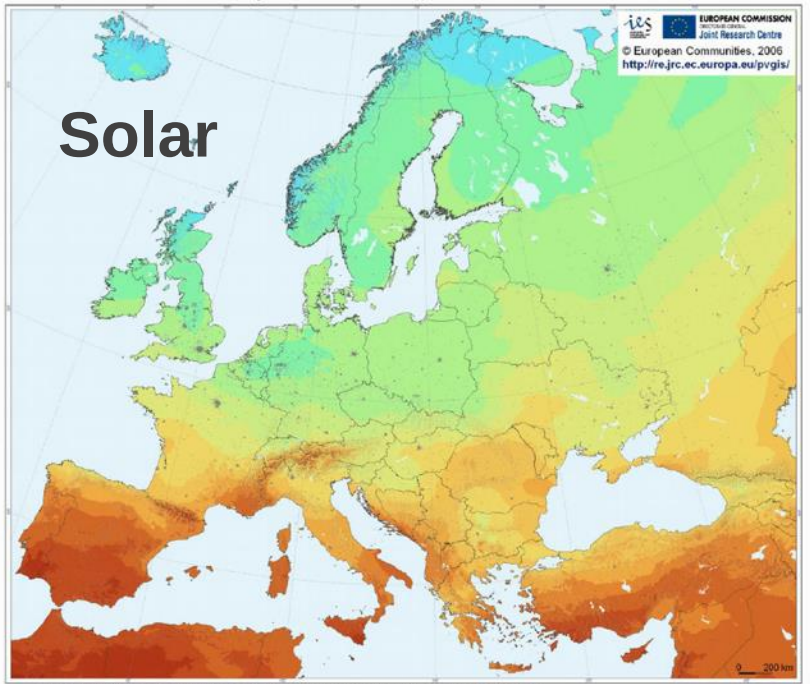


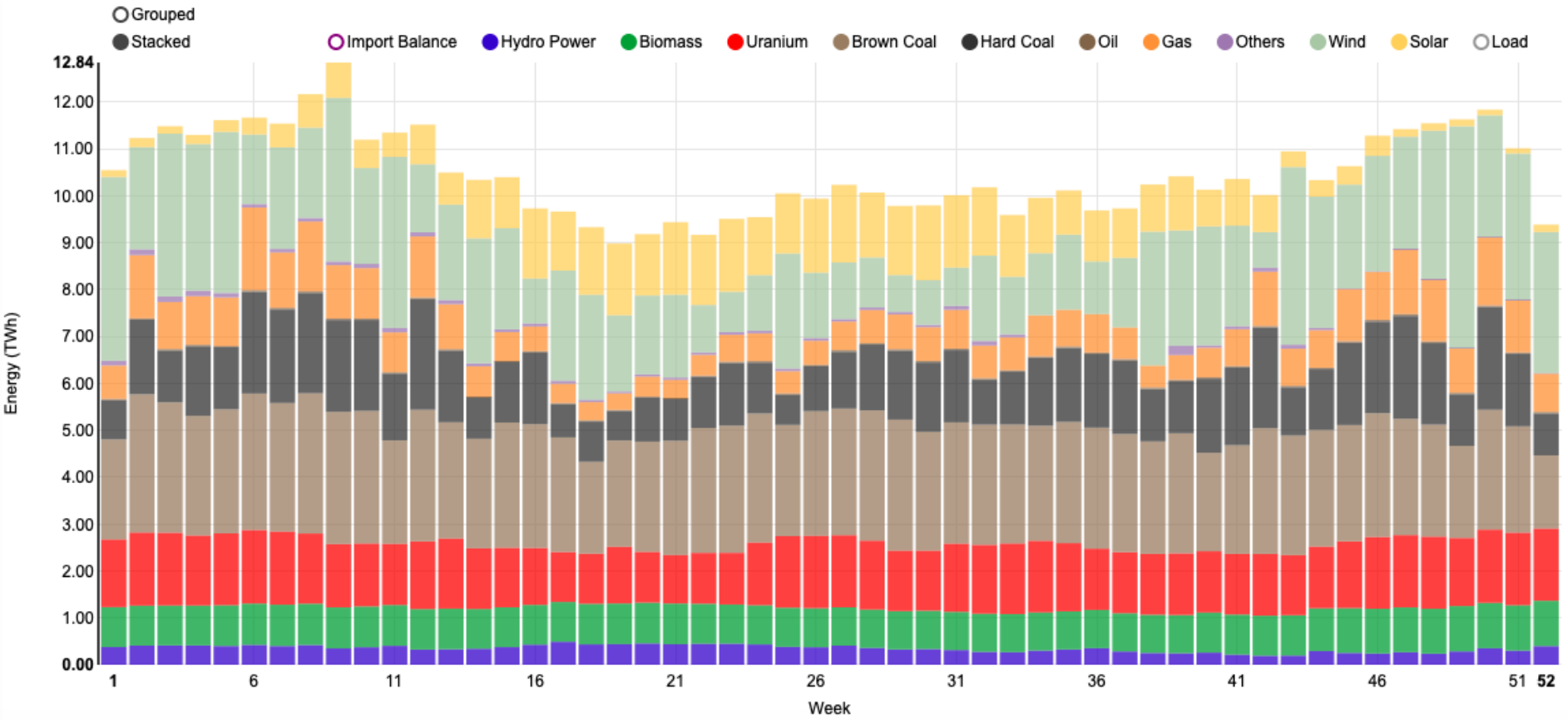


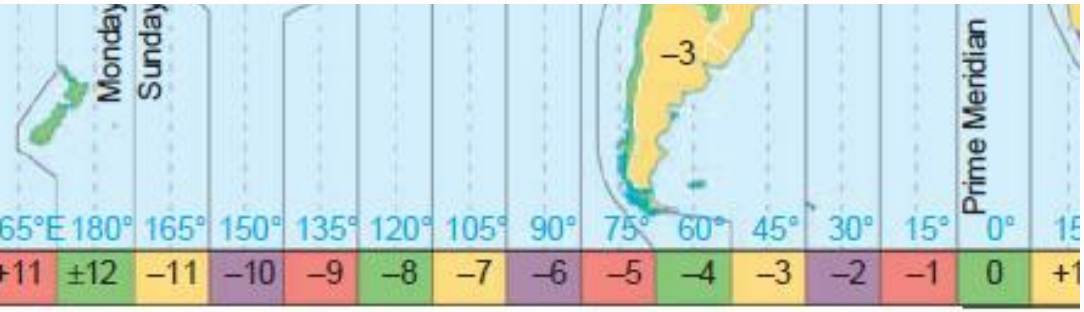
1.16 Time zones of the world

Photovoltaic Solar Electricity Potential in European Countries



Weekly electricity generation in Germany in 2018





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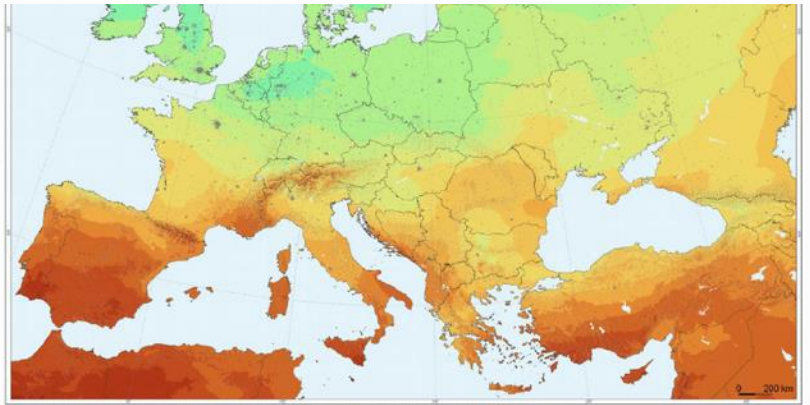
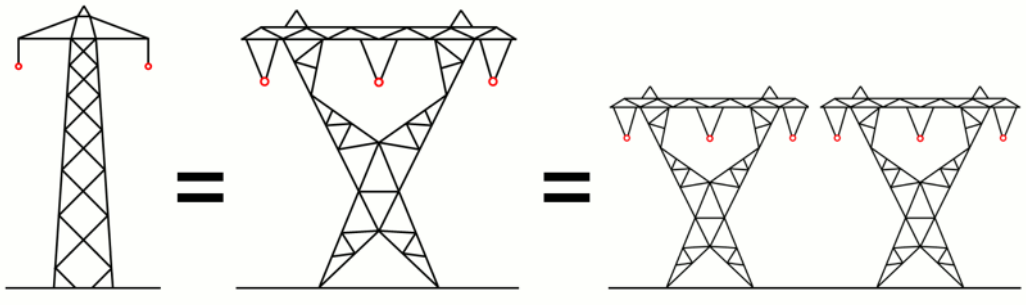
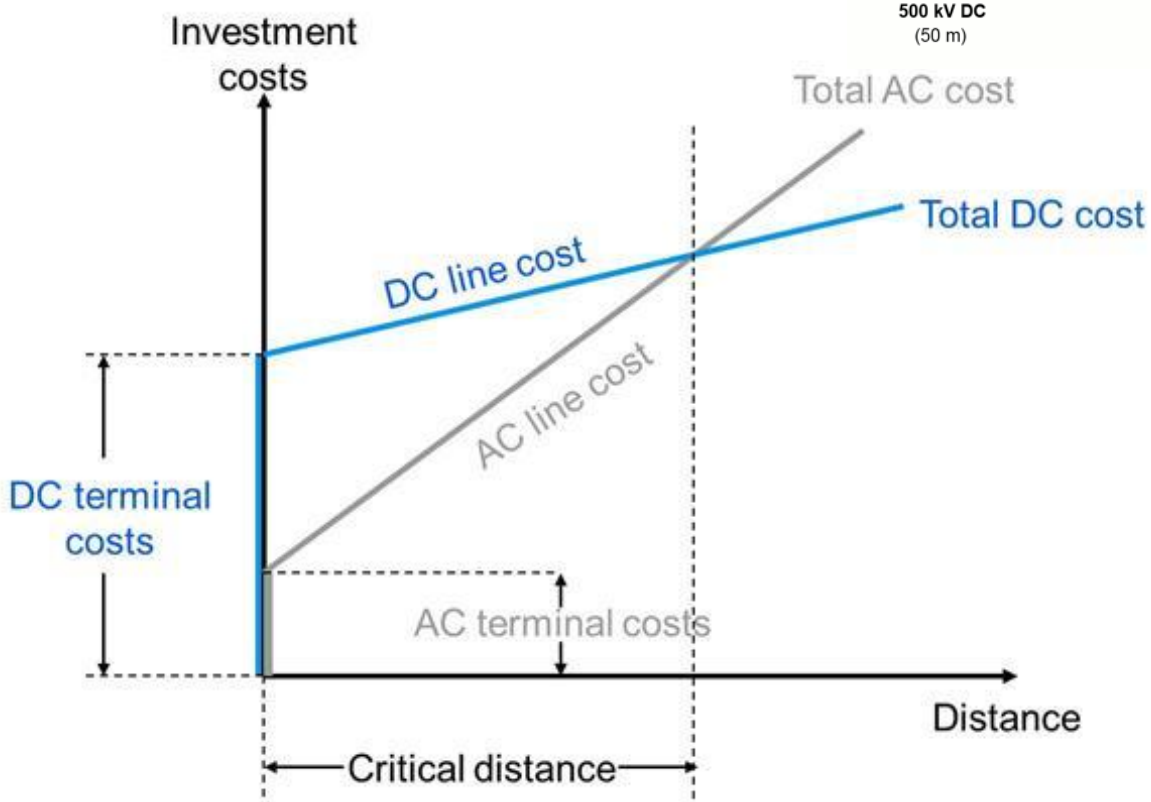


How far can electricity be sent?





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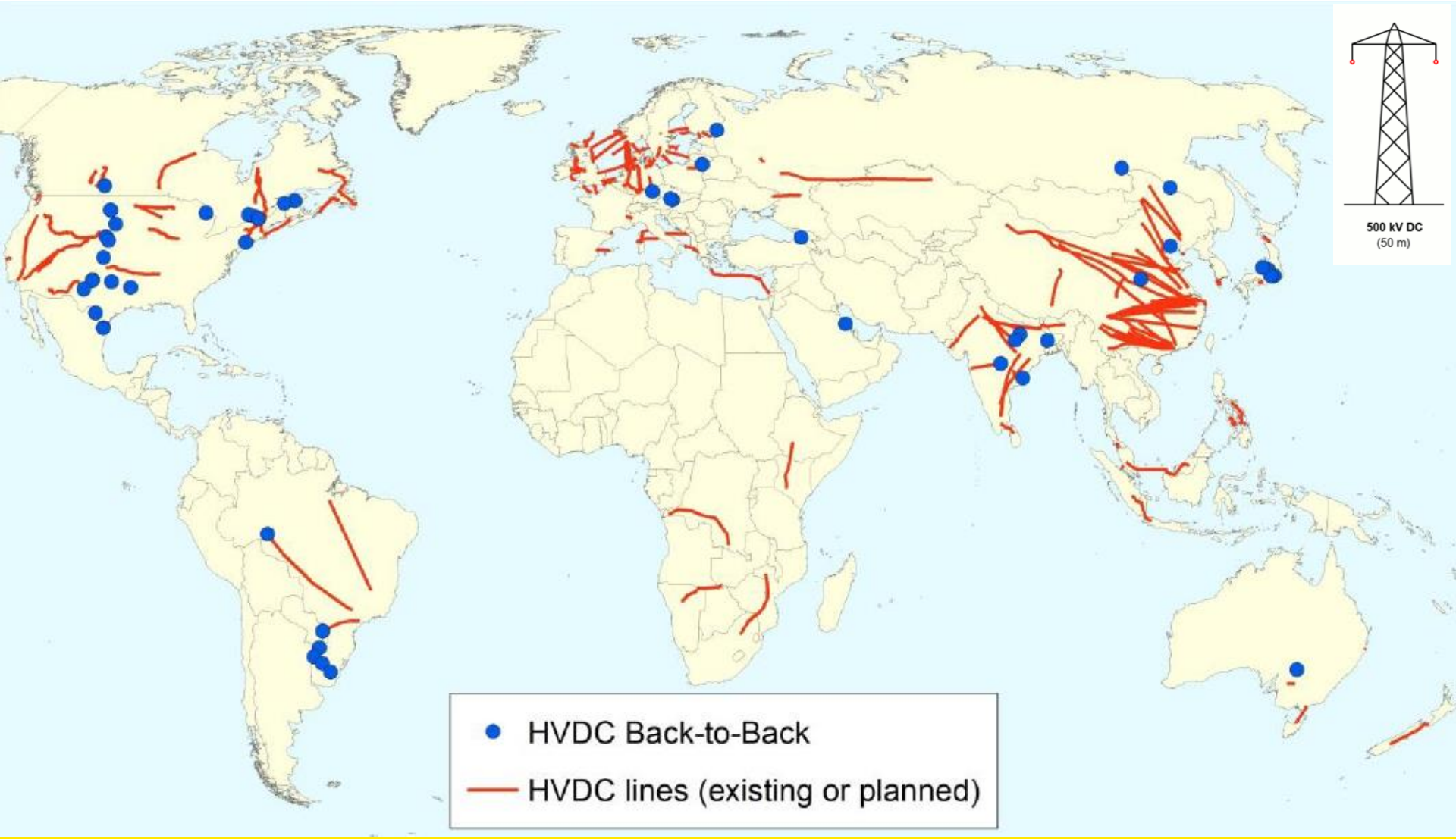

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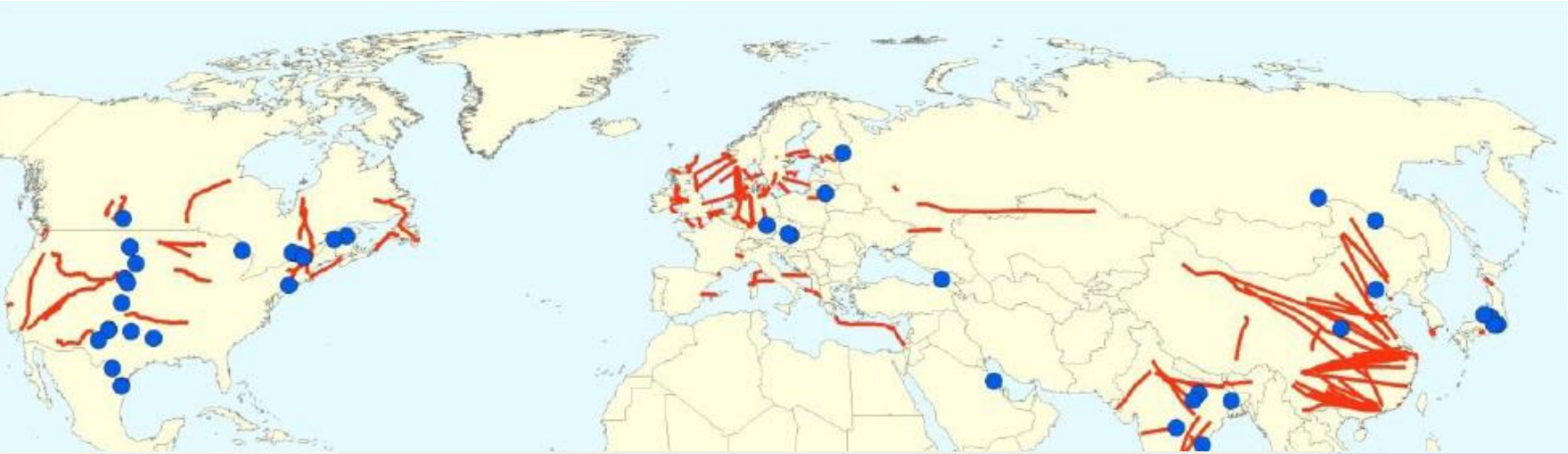
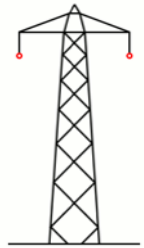




A Record-Setting HVDC System

12
gigawatt
transmission capacity

equivalent to the output of about 12 large conventional power plants

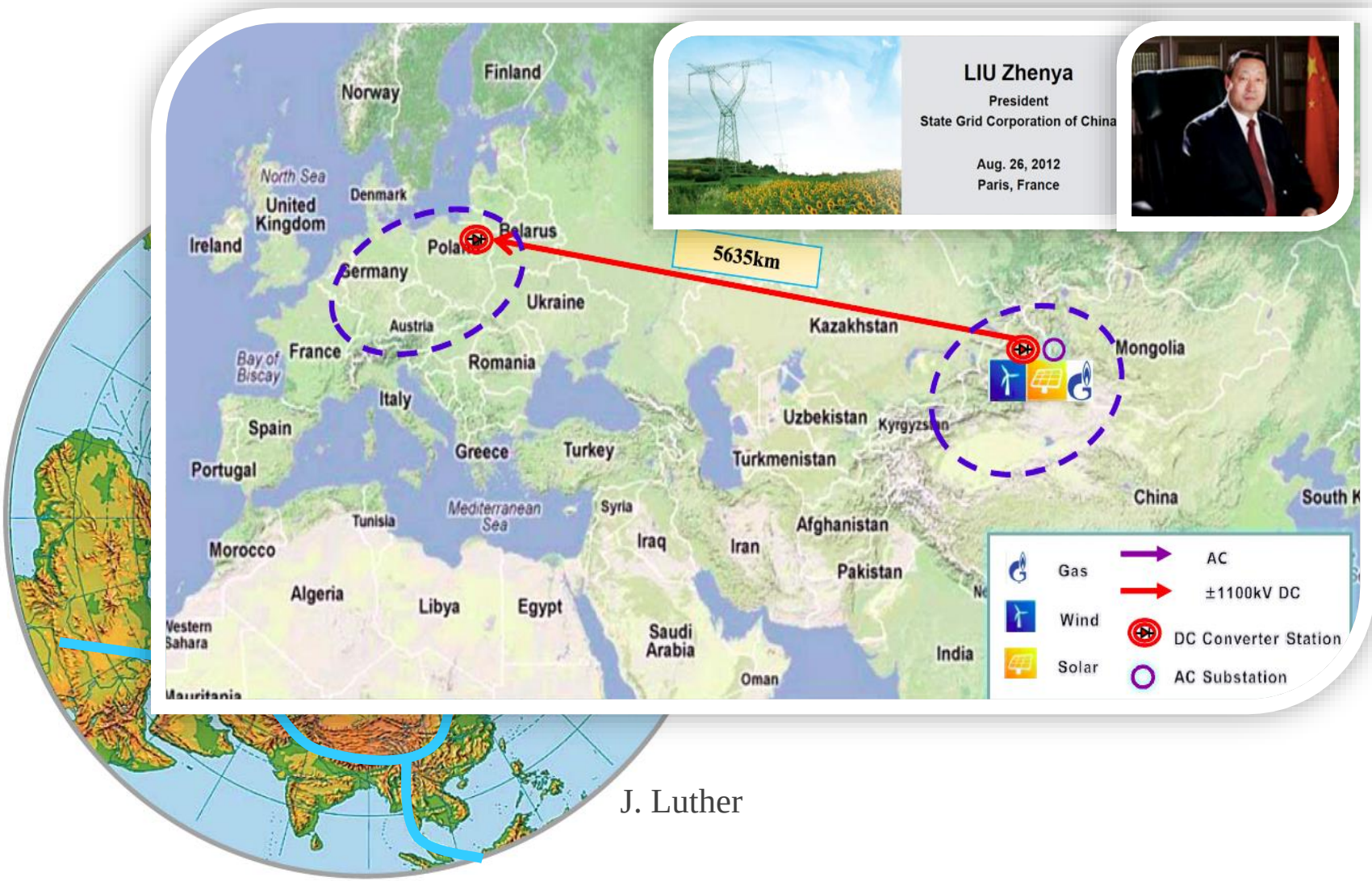
7 transformers with
1,100
kilovolts
DC voltage

Changji
Beijing
Length: 3,284 km
PEOPLE'S REPUBLIC OF CHINA
Xi'an
Guquan

37.5
Percent
increase in transmission voltage

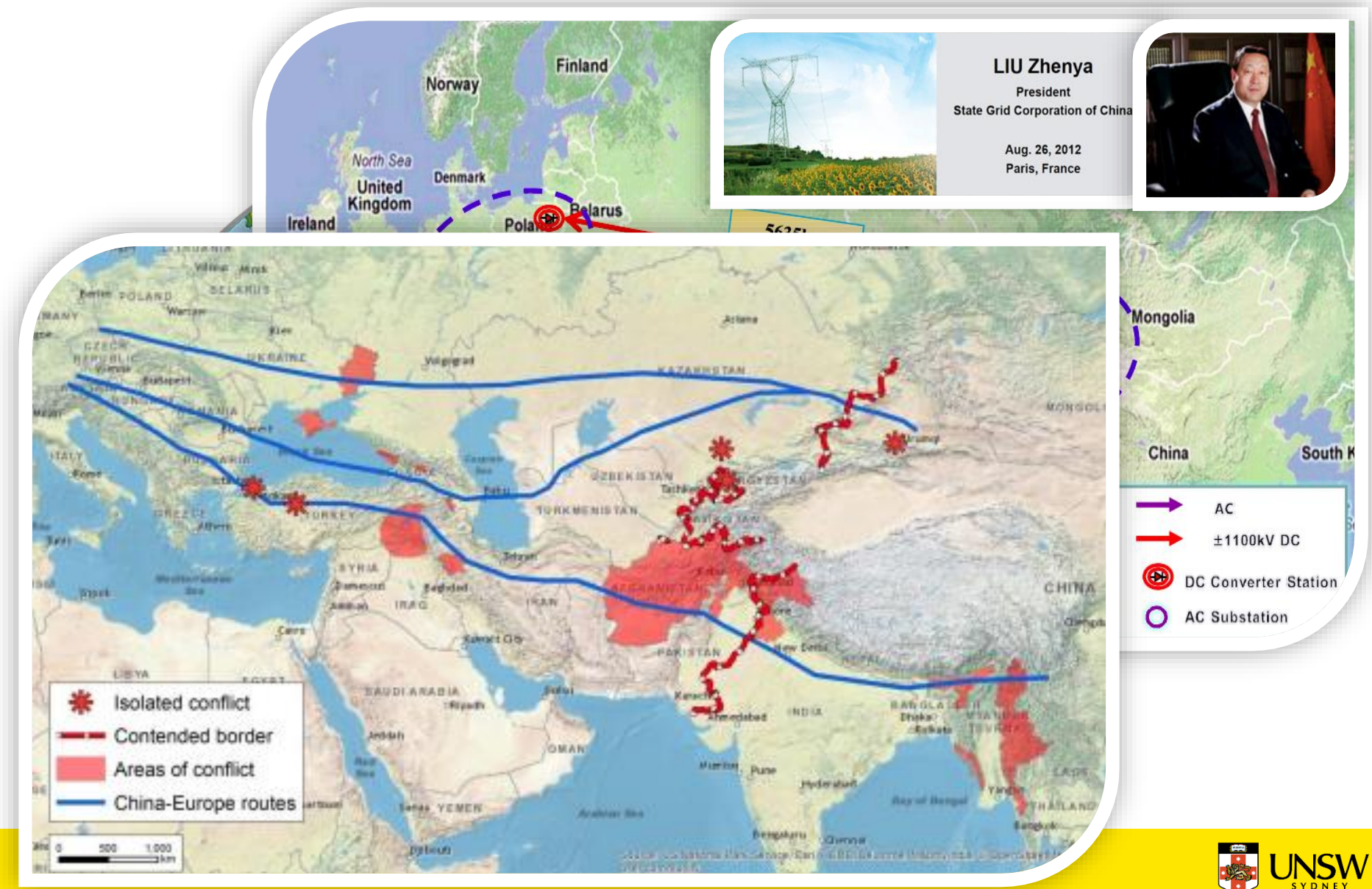
In comparison to 800 kV – the highest voltage possible until now on HVDC lines

Sun always shining somewhere

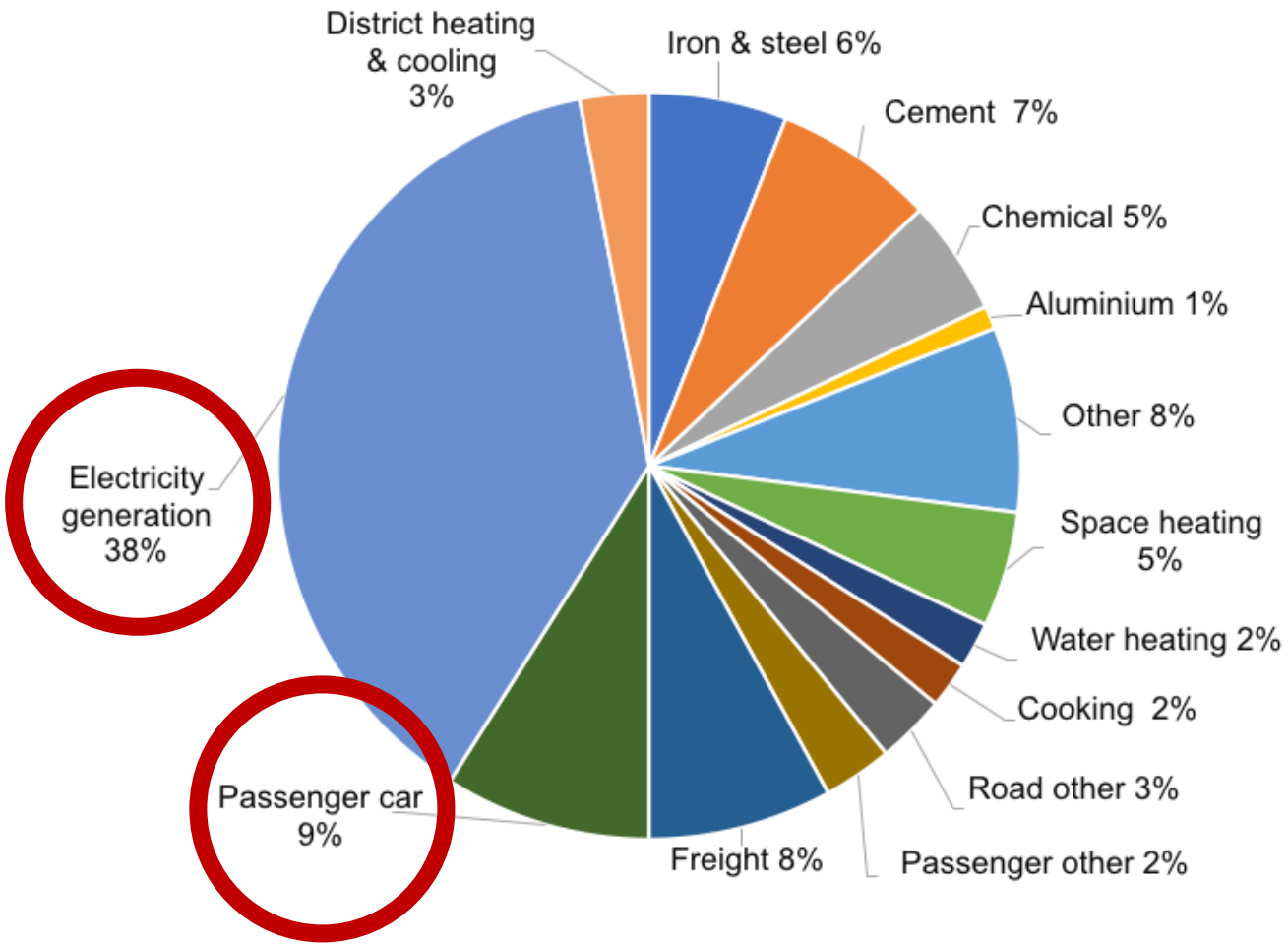


J. Luther

Sun always shining somewhere



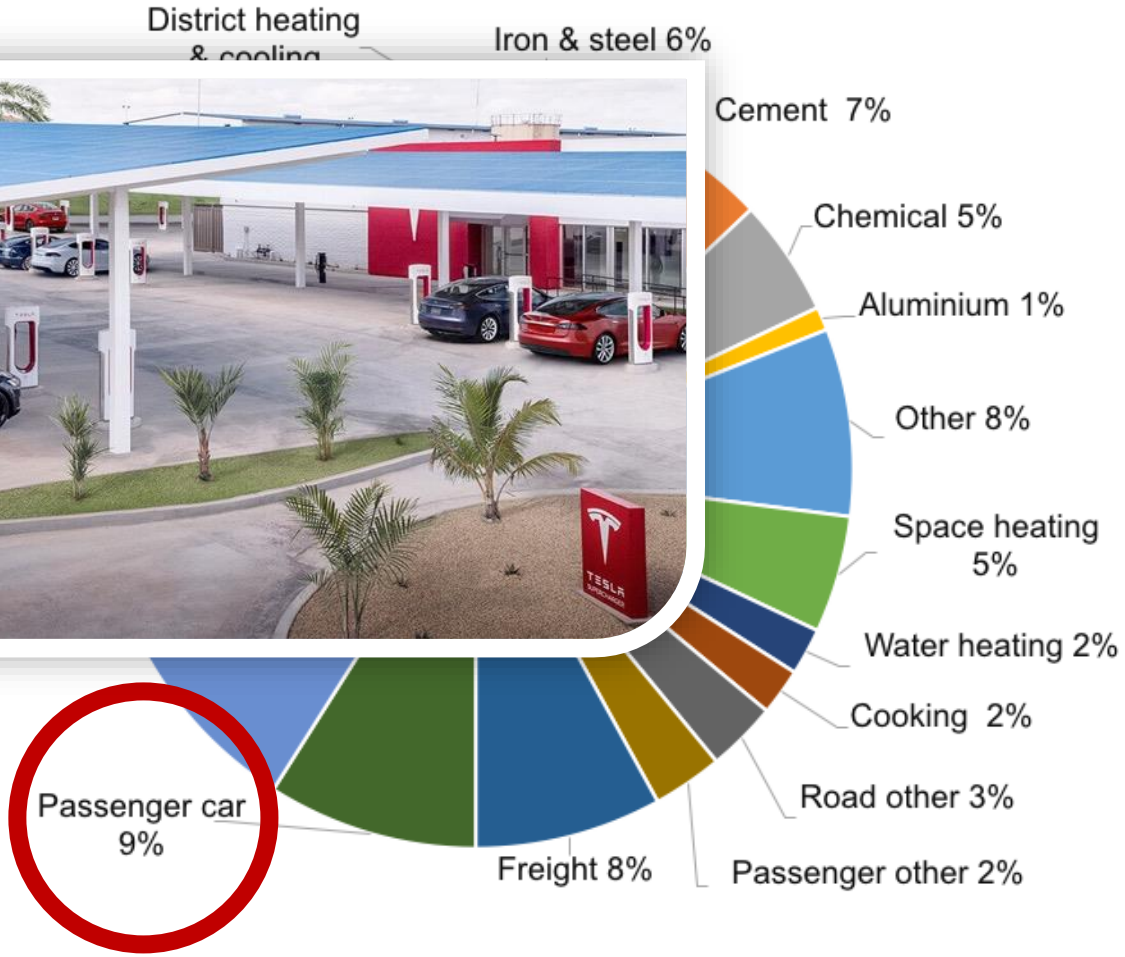
Source of global CO_2 emissions



IRENA
International Renewable Energy Agency

UNSW SYDNEY

Source of global CO_2 emissions



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International Renewable Energy Agency

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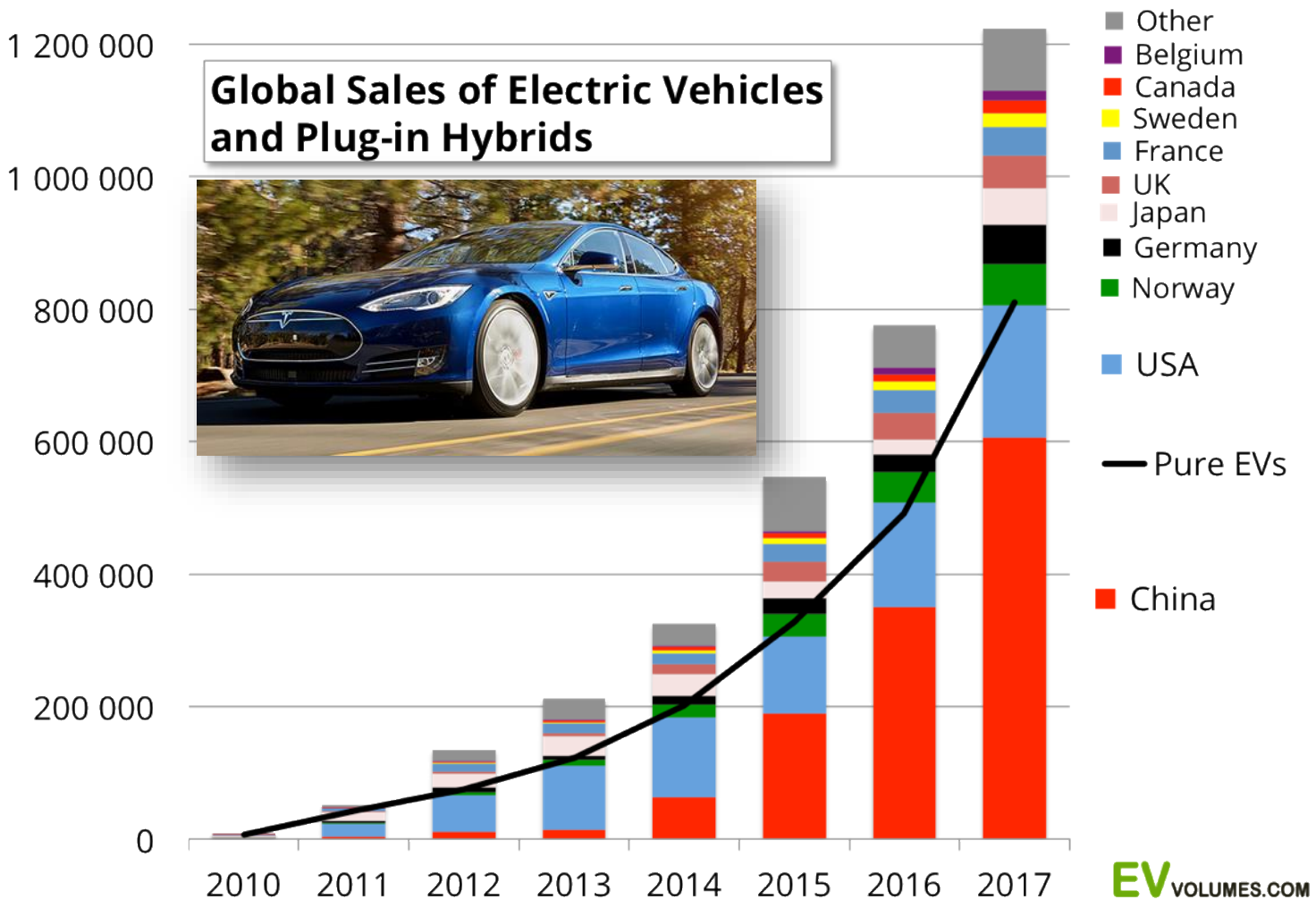
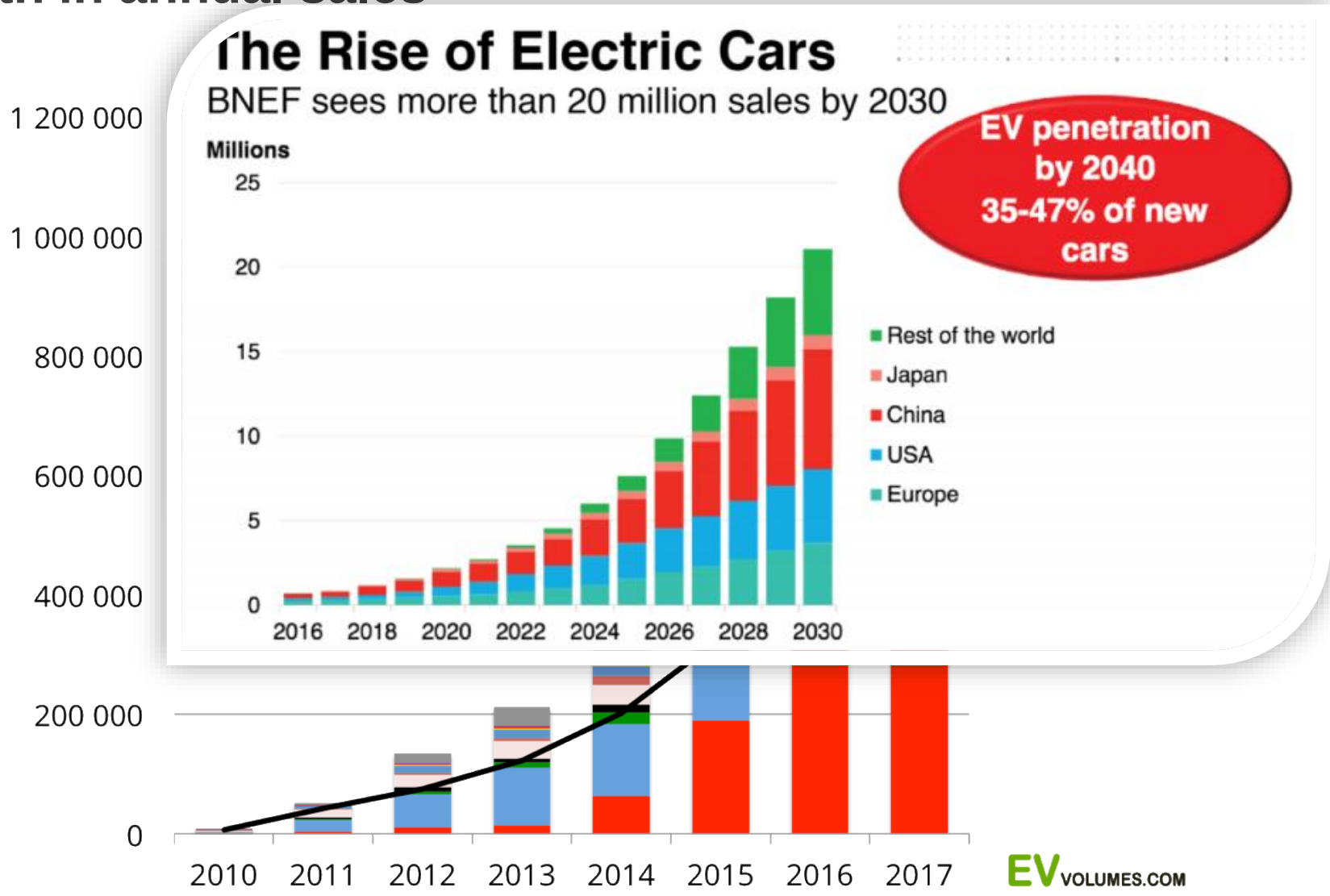
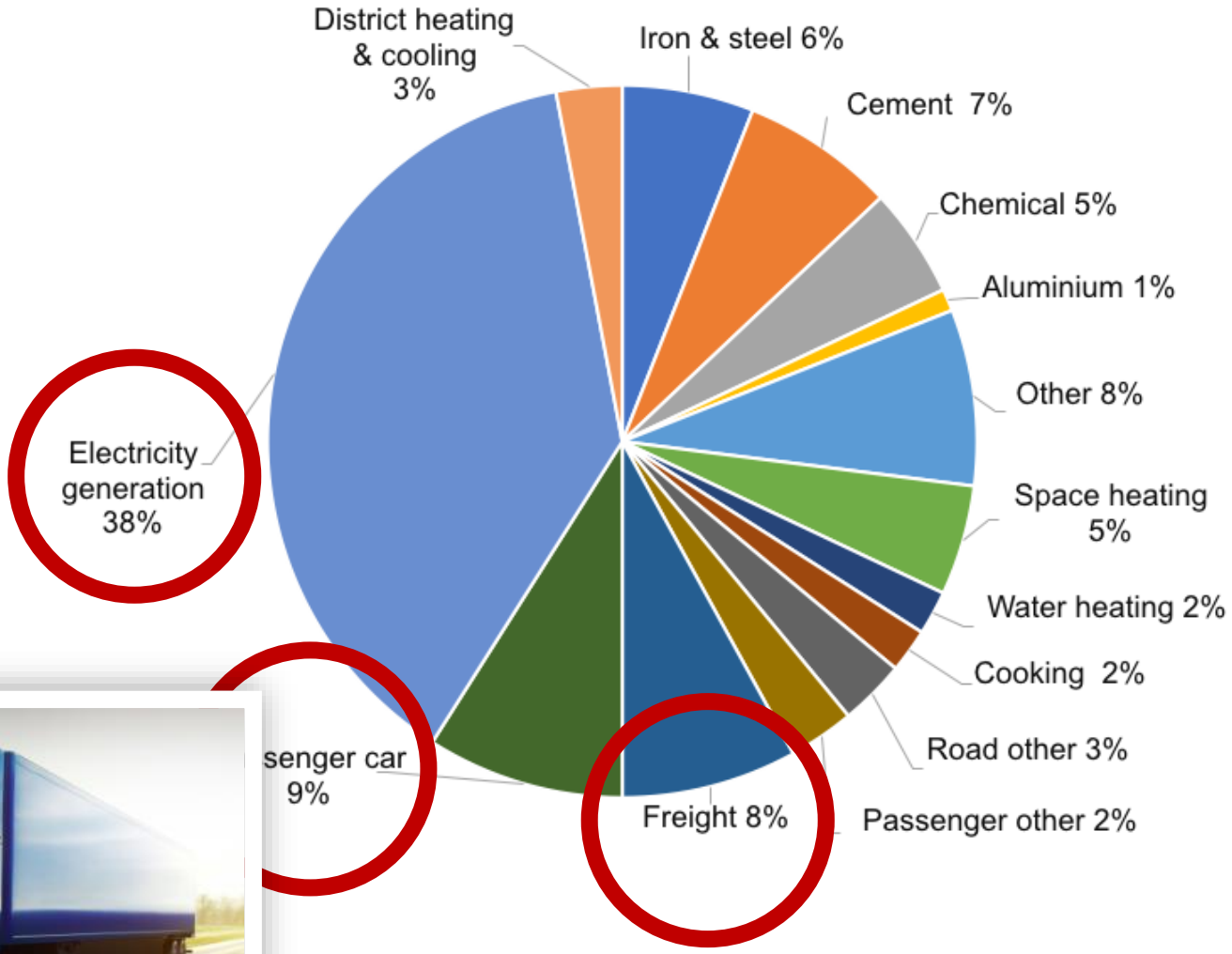
Growth in annual sales

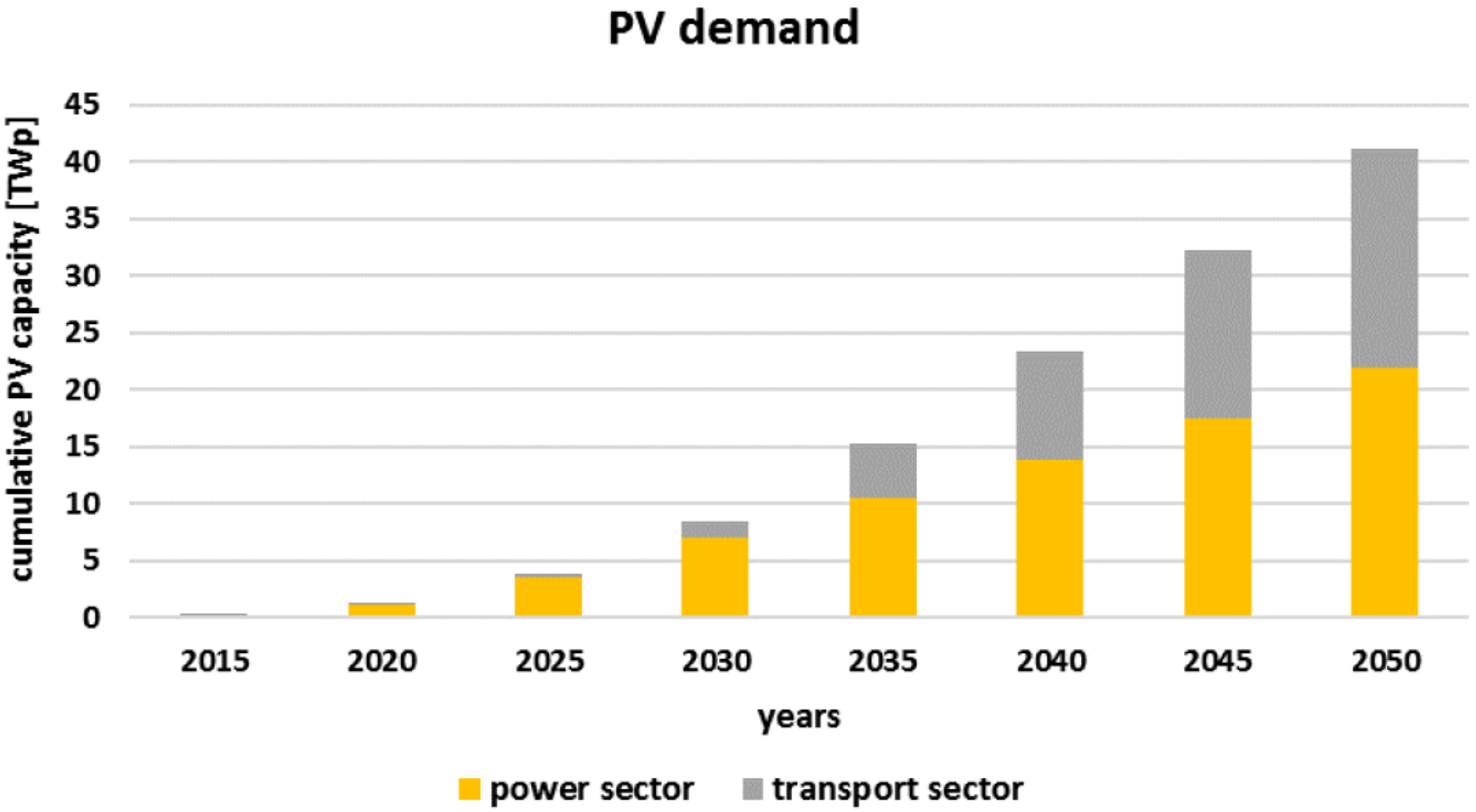


Growth in annual sales

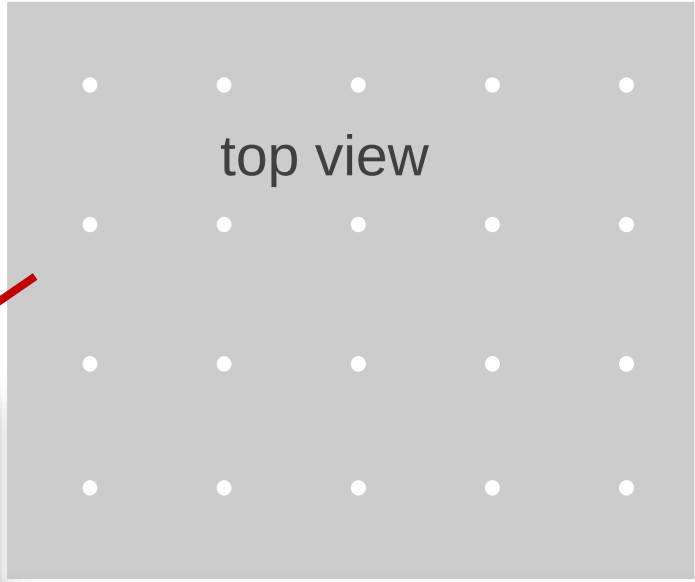


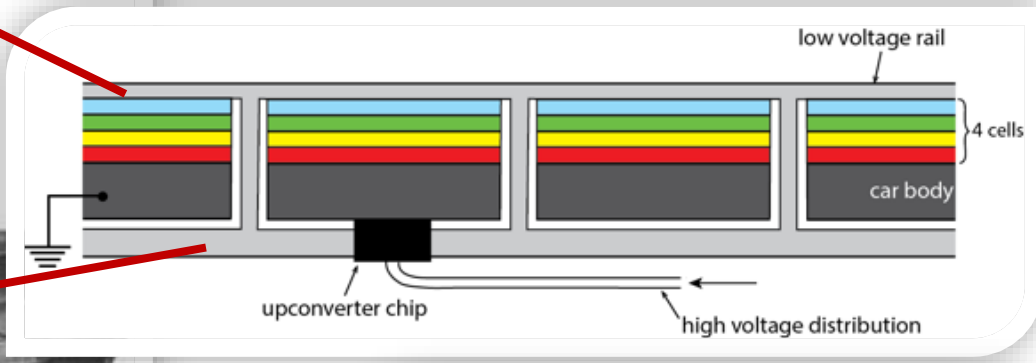
Source of global CO_2 emissions



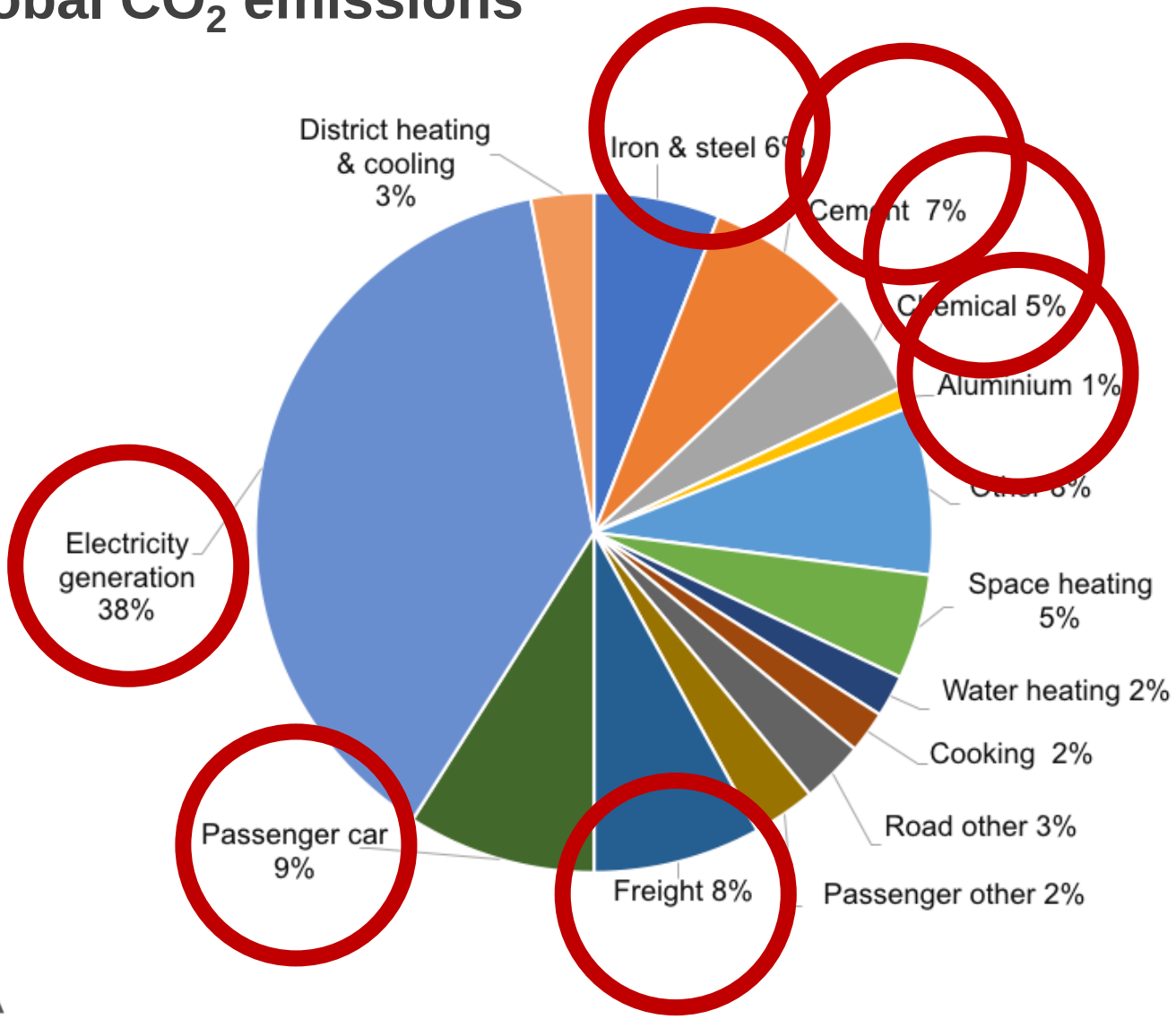


Parallel connection





Source of global CO_2 emissions



IRENA
International Renewable Energy Agency

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Terawatt PV demand by 2050

PV demand by sectors

- 22.0 TWp power sector, structured as of today, uncertainty: low
- 19.2 TWp transport sector, uncertainty: moderate (full hourly modeling still to be done)
- 18.0 TWp chemical industry, uncertainty: high (all basic feedstock chemicals to be investigated)
- 4.0 TWp desalination demand, uncertainty: moderate/ high (resolving water-energy nexus possible)
- 3.0 TWp CO_2 direct removal, uncertainty, moderate (uncertainties in technology up-scaling)
- ? TWp heat sector, solar conditions not so good in times of very low temperature
- ? TWp steel industry, switch to H_2-DRI is open secret
- ? TWp other industry, e.g. material refining (Aluminium, Copper, etc.), cement, etc.

~80 TWp of total PV demand by 2050 seems to be a possible future

Please do not forget, no one has yet understood what 10 USD/MWh PV generation cost really means!

ARENA

Australian Government

Australian Renewable Energy Agency

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