Australian Government

# Journey from Gen III/III+ to Gen IV Reactors


Dr Adi Paterson

Australian Nuclear Science & Technology Organisation


*EA Nuclear Engineering Panel: 22 November, 2017*

# ANSTO Putting Science to Work

OPAL Research Reactor

Centre For Neutron Scattering

Nuclear Materials Research

Advisor to Government

Australian Synchrotron

Centre for Accelerator science

Nuclear Fuel Cycle Research

AINSE


Argonne National
Laboratory (West)
Idaho, USA

*EBR-1 First Nuclear Electricity - December 20 1951*


GEN IV International Forum℠

# GIF Timeline (Australia)

- Intention to apply in April 2007
- Application halted (change in Government) in late 2007
- Government supports bid to join the GIF in March 2015 with bi-partisan support
- Petition presented to GIF Policy Group in October 2015
- GIF Policy Group Delegation visit to Australia in Feb 2016


GIF Policy Group Delegation to Australia, 2-4 February 2016

From Lyndon Edwards: Australia's Participation in the Generation IV International Forum (GIF)

# Nuclear Energy Agency Announcement

## Australia accedes to the GIF Framework Agreement

On 14 September 2017, Australia deposited its ***instrument of accession*** to the Generation IV International Forum (GIF) ***Framework Agreement***……. Australia became the 14th member of the GIF on 22 June 2016 when it signed the GIF Charter.

Acceding to the ***Framework Agreement*** will allow Australia to become ***actively engaged in R&D projects*** related to Generation IV systems, particularly in R&D projects on advanced materials.

# International Context

Instruments for Australia in Nuclear Power

- IAEA/NEA (Fission): Small Modular Reactors
- Fusion: **ITER** and **INTERNATIONAL TOKAMAK PHYSICS ACTIVITY (ITPA)**
- Generation IV International Forum
- China: SINAP partnership (renewal?)

=

Towards a strategic research and technology framework?

# Generations of Nuclear Energy

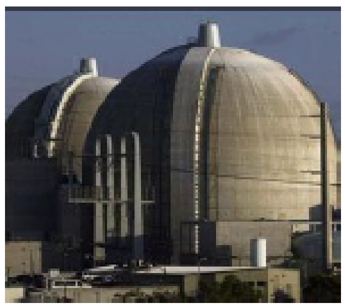
### Generation I

Early Prototypes

- Shippingport
- Dresden
- Magnox

### Generation II

Commercial Power



- PWRs
- BWRs
- CANDU

### Generation III

Advanced LWRs

- CANDU 6
- System 80+
- AP600

### Generation III+

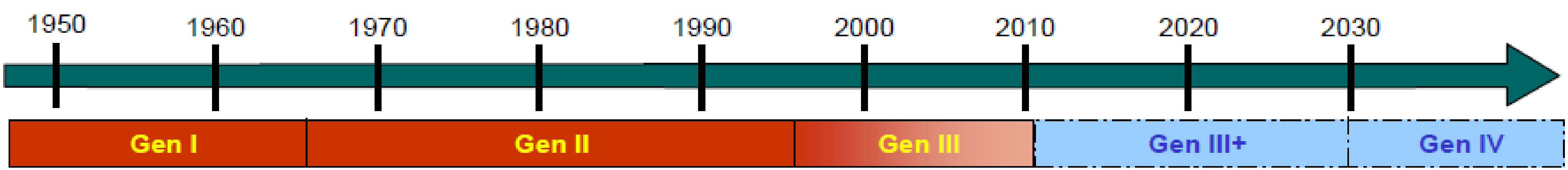
Evolutionary Designs

- ABWR
- ACR1000
- AP1000
- APWR
- EPR
- ESBWR

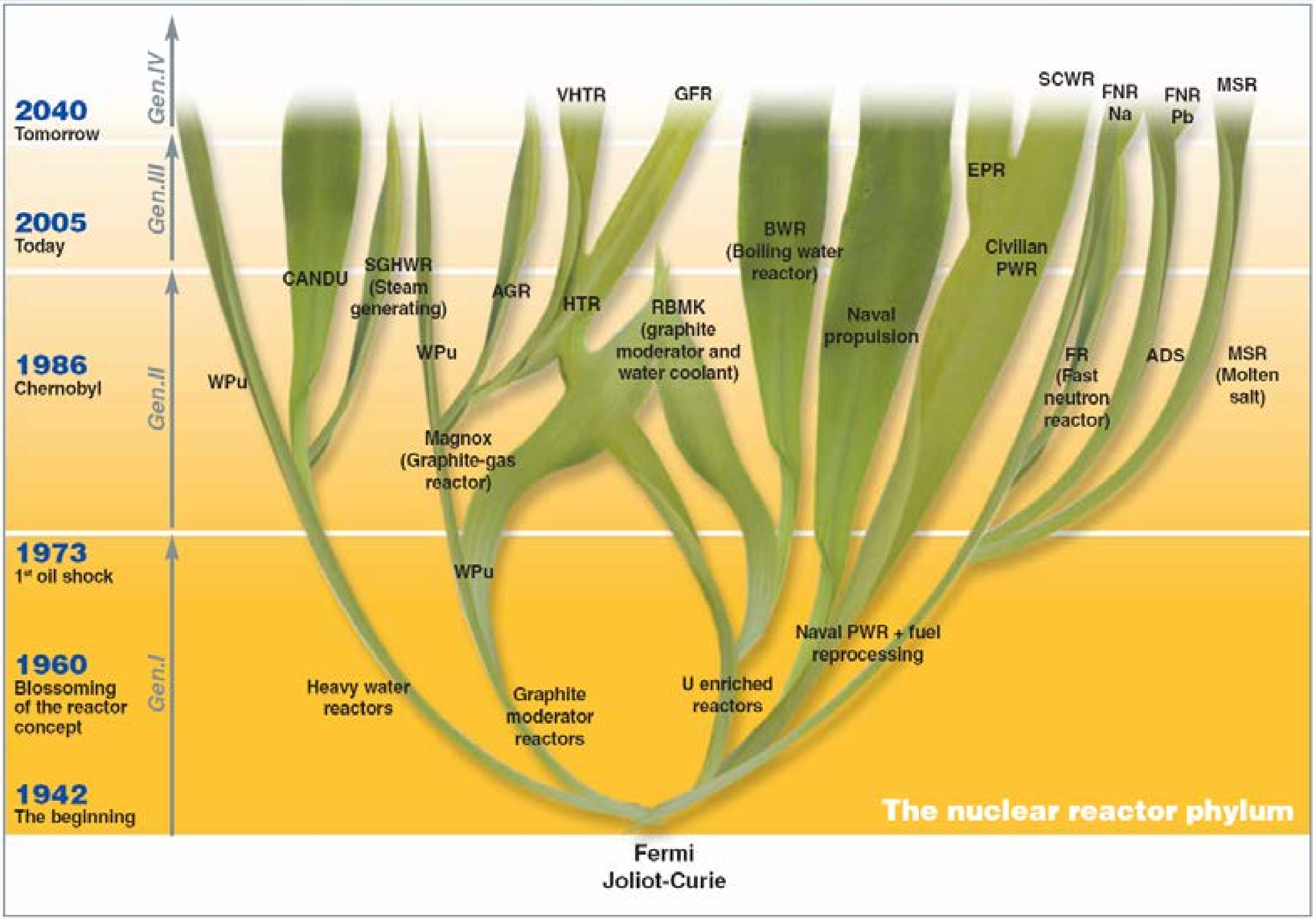
### Generation IV

Revolutionary Designs

- Safe
- Sustainable
- Economical
- Proliferation Resistant and Physically Secure



# Tree of Nuclear Power Reactors




From G. Cognet: The different generations of nuclear reactors From Generation-1 to Generation-4

# Gen III Objectives

- ABWR 1996
- Active Safety – reduced core damage frequency
- Improved Fuel Technology
- Design Life Extension 60-100 years
- Thermal efficiency
- Standardisation

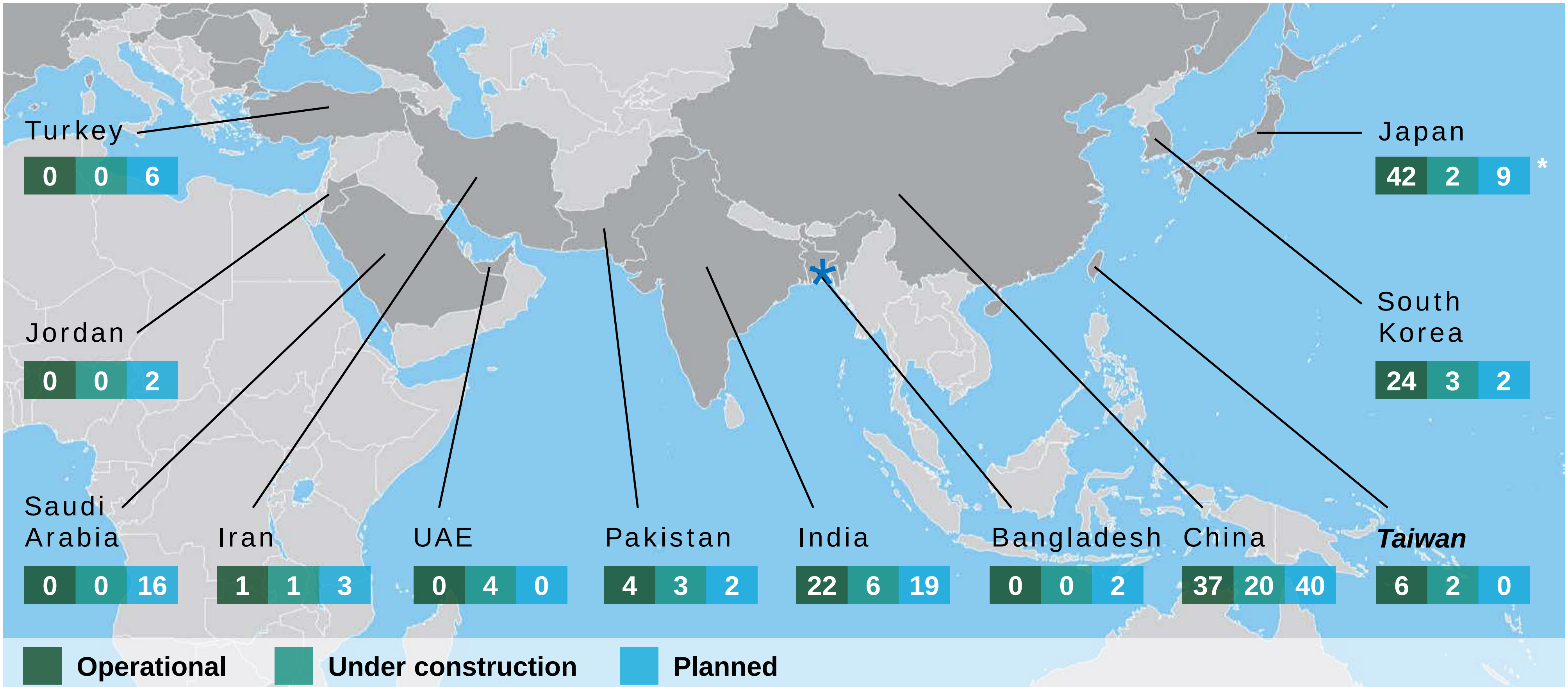
# Gen III+ Objectives

- VVER-1200/392M 2017
- Superior Thermal Efficiency
- Passive safety systems
  - Gravity fed cores, convective cooling and condensation
- Standardised designs “modularity”
- Accident tolerant fuel
- Operational design life 50 to 100 years

# III/III+ to IV Global Nuclear Capacity

- Significant shifts since 2013
- The “models” are changing
- The countries are changing
- New insights:
  - Predictable supply chains (the Russian model)!
    - Lifecycle contracts with spent fuel return
  - SMRs spin or substance?

# Reactors planned, under construction and operational



# Generations of Nuclear Energy

## Advanced reactors

Generation IV

Revolutionary Designs

## Older Reactors (no more builds)

Generation I

Early Prototypes

- Shippingport
- Dresden
- Magnox

Generation II

Commercial Power

- PWRs
- BWRs
- CANDU

## New Reactors (current builds)

Generation III

Advanced LWRs

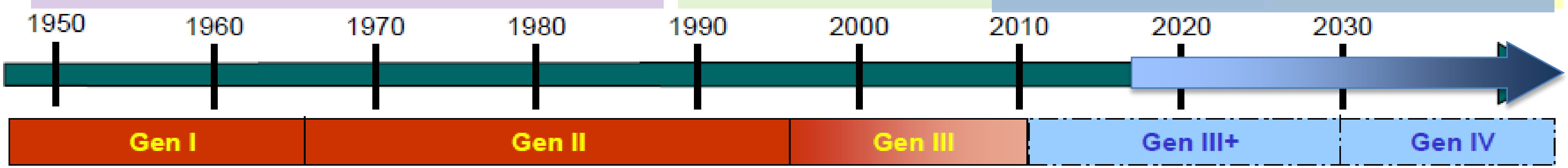
- CANDU 6
- System 80+
- AP600

Generation III+

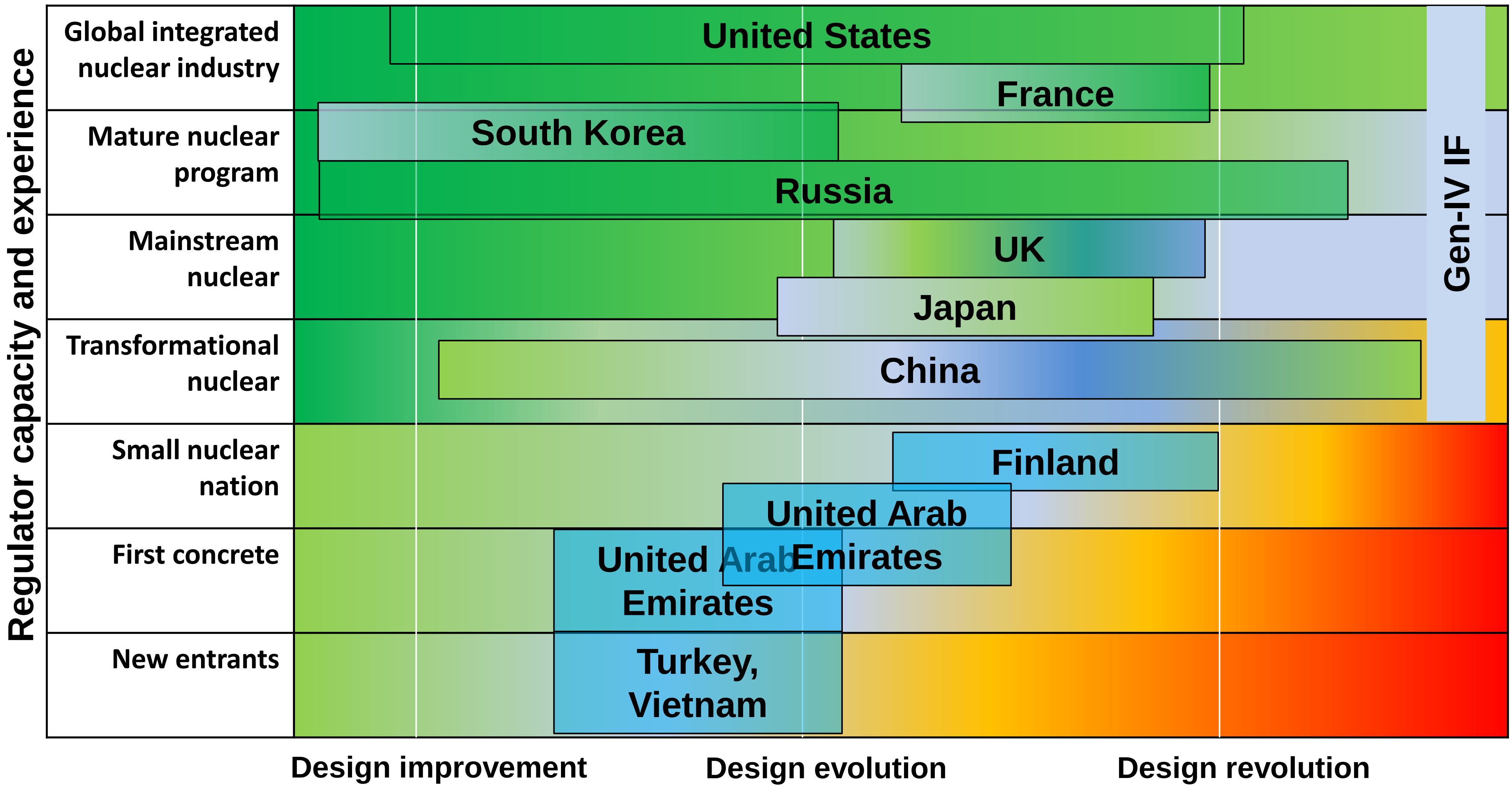
Evolutionary Designs

### Small Modular Reactors

| Gen III+ | Gen IV |
|---|---|
| Integral-PWRs | HTGRs |
| | MSRs |
| | SFRs |
| | LBFRs |

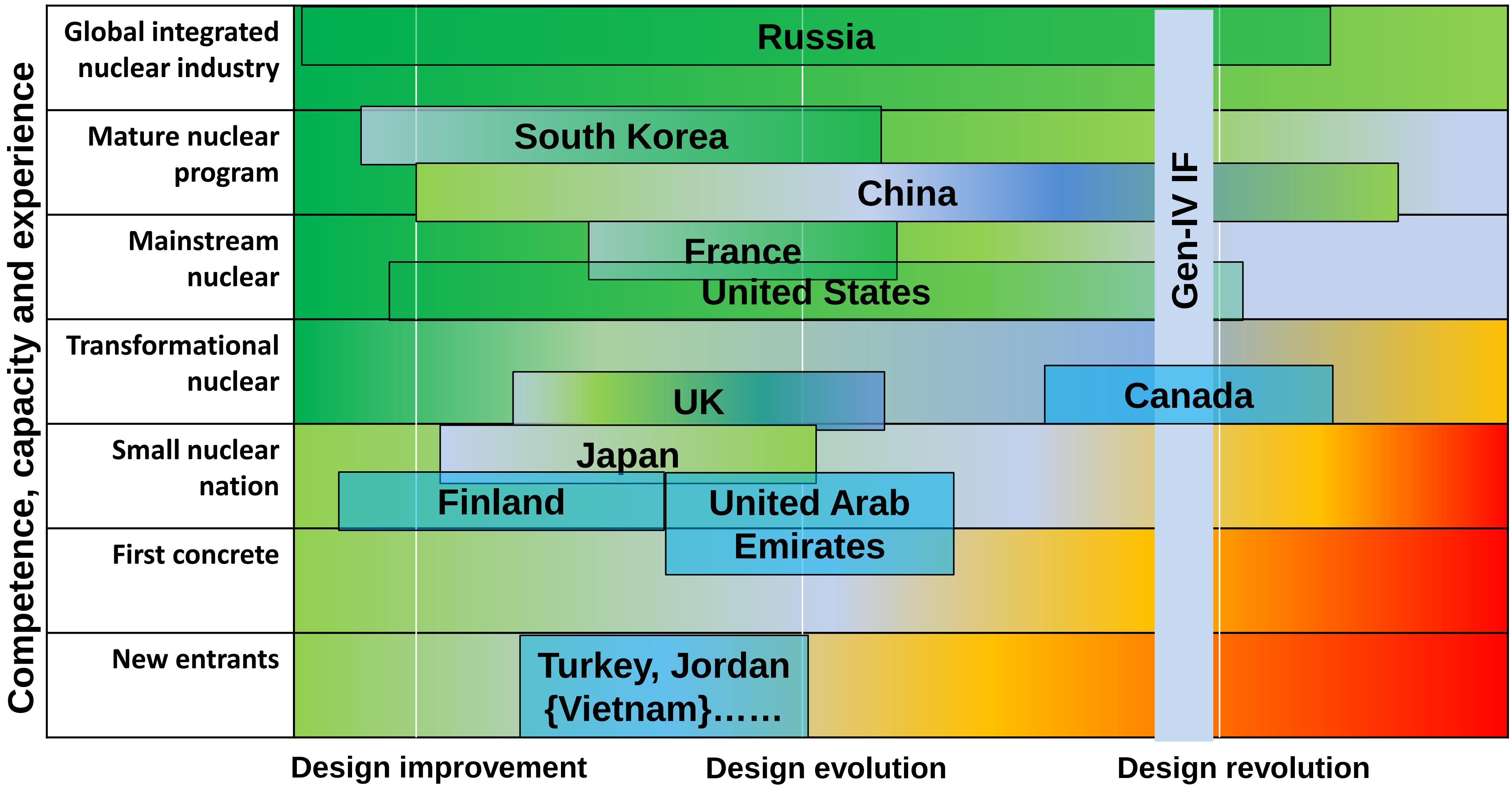


# My view in 2013
# Design maturity and regulators



# 2017

# Aspiration: Design maturity and ~~regulators~~



# Genesis of Generation IV Concepts

- In 1999, low public and political support for nuclear energy
  - Oil and gas prices were low
- USA Proposed a bold initiative in 2000
  - The vision was to leapfrog LWR technology and collaborate with international partners to share R&D on advanced nuclear systems
  - Oil prices jumped soon thereafter
- Gen IV concept defined via technology goals and legal framework
  - Technology Roadmap released in 2002
    - 2 year study with more than 100 experts worldwide
    - Nearly 100 reactor designs evaluated and down selected to 6 most promising concepts
  - First signatures collected on Framework Agreement in 2005; first research projects defined in 2006

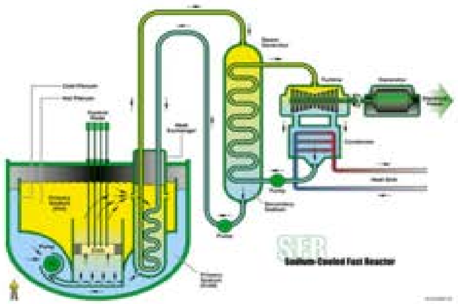
***"This may have been the first time that the world came together to decide on a fission technology to develop together."***
William Magwood IV, First Chairman of the Generation IV International Forum

From John Kelly: GIF Webinar series at: www.gen-4.org/gif/jcms/c_84314/webinar-series-1-atoms-for-peace-the-next-generation

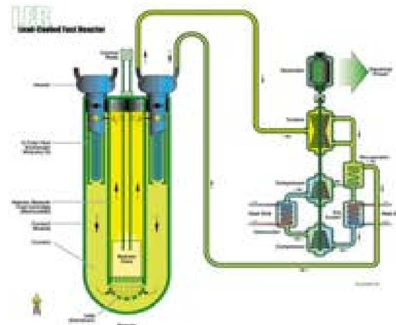
# Generation IV Goals

- Safety and Reliability
  - Very low likelihood and degree of core damage
  - Eliminate need for offsite emergency response
- Sustainability
  - Long term fuel supply
  - Minimise waste and long term stewardship burden
- Proliferation Resistance and Physical Protection
  - Unattractive Materials diversion pathway
  - Enhanced physical protection against terrorism
- Economics
  - Life cycle cost advantage over other energy sources
  - Financial risk comparable to other energy sources

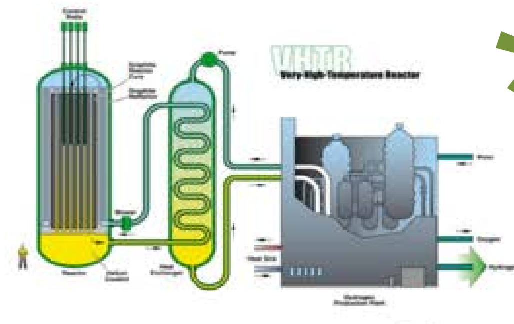
# Generation IV reactors



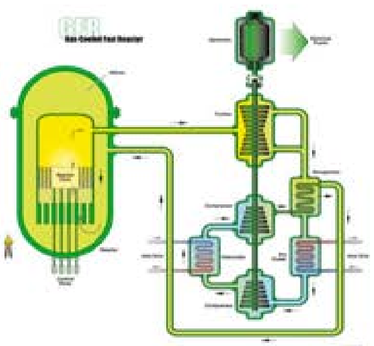

Sodium Fast Reactor



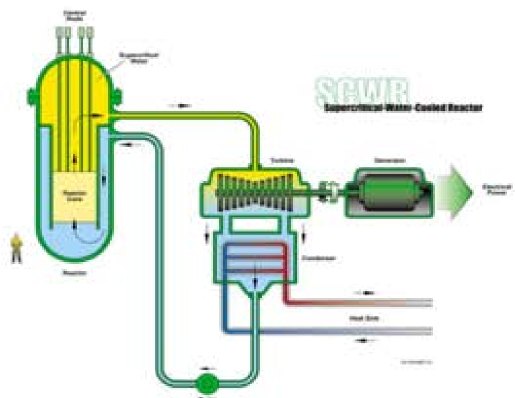

Lead Fast Reactor



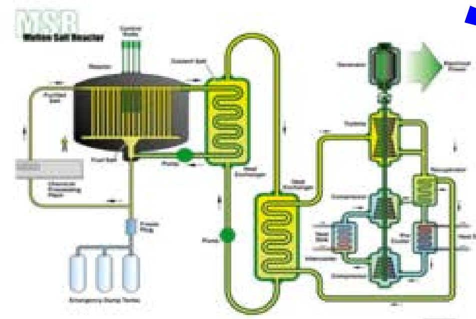

Very High Temperature Reactor




Gas-Cooled Fast Reactor




Super Critical Water Cooled Reactor

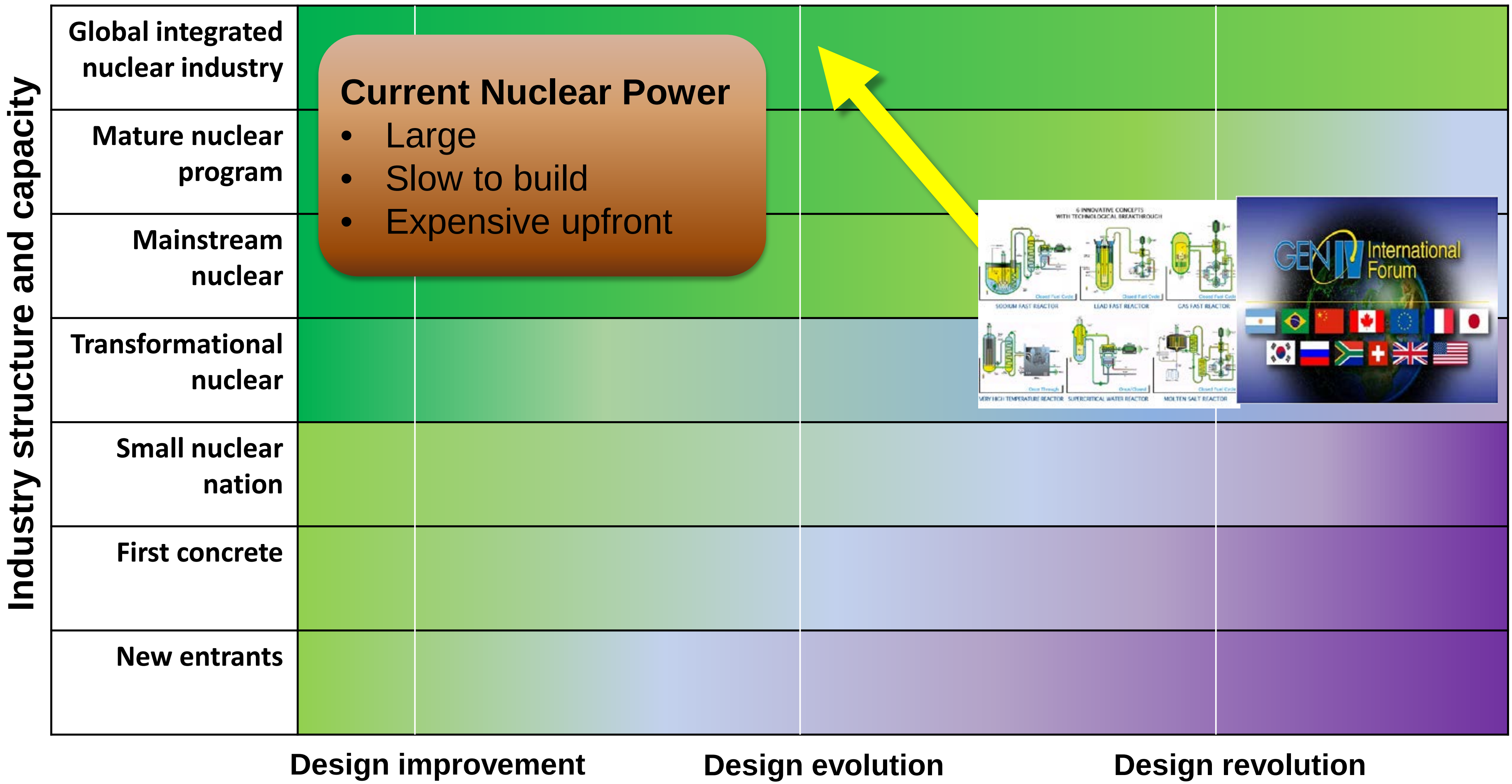



Molten Salt Cooled Reactor

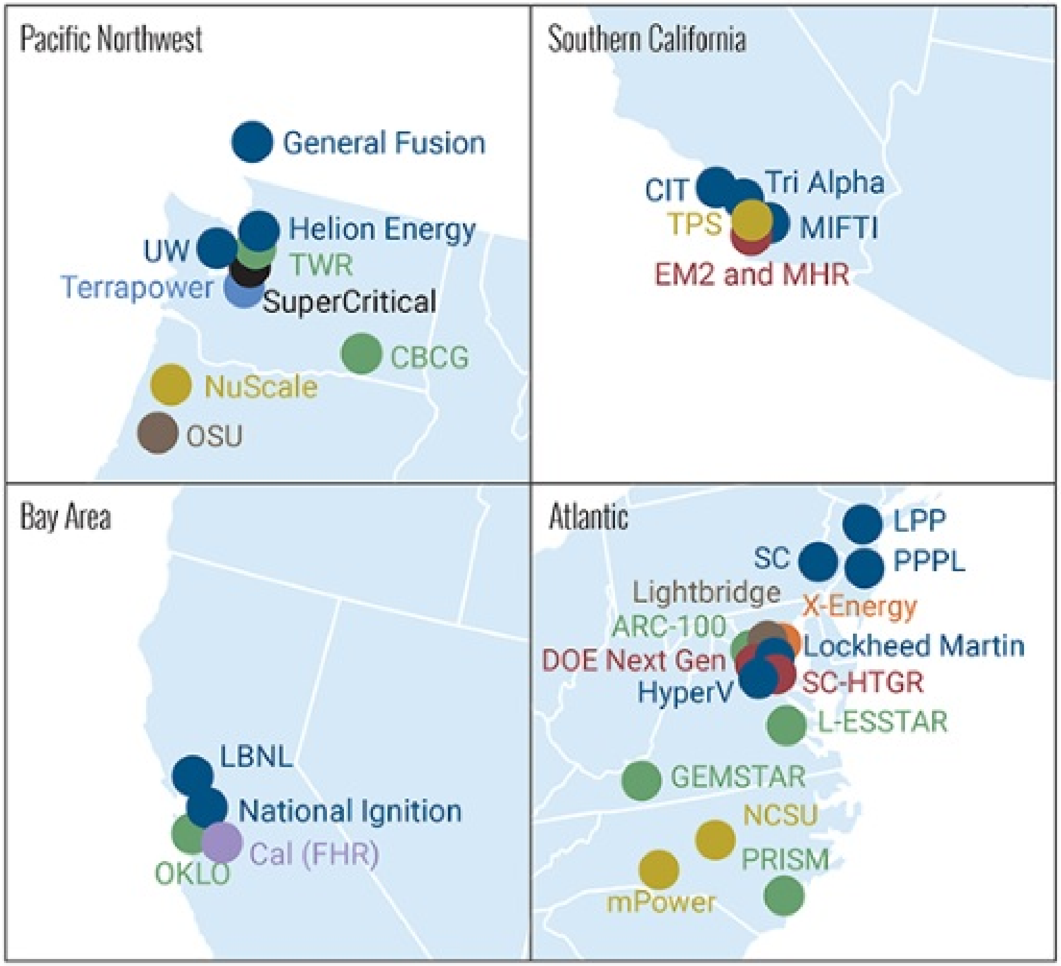
# Gen-IV Market Status Developments

- Terrestrial Integral Molten Salt Reactor (Canada)
- Terra-Power (US-China)
- HTR-PM in China (VHTR)
- BN-800 (Sodium Fast Reactor) Russia-China

# Gen-IV and the developmental risk space



# US Clusters




## Reactor Design Types

- Molten Salt Reactor
- Fluoride Salt-cooled High Temperature Reactor
- Liquid Metal-cooled Fast Reactor
- High Temperature Gas Reactor
- Pebble Bed Reactor
- Nuclear Battery Reactor
- Designs Advanced Nuclear Fuels
- Small Modular Reactor
- Fusion Reactor
- Super-Critical $CO_2$ Reactor
- Accelerator Driven System

# 2016 HTR-PM China

Source: WNA

# BN-800

# Gen-IV Australia Ambitions

- First membership by a non-nuclear power country
- Nuclear materials focus
- Safety cases
- Economics
- …… more focus on Waste management

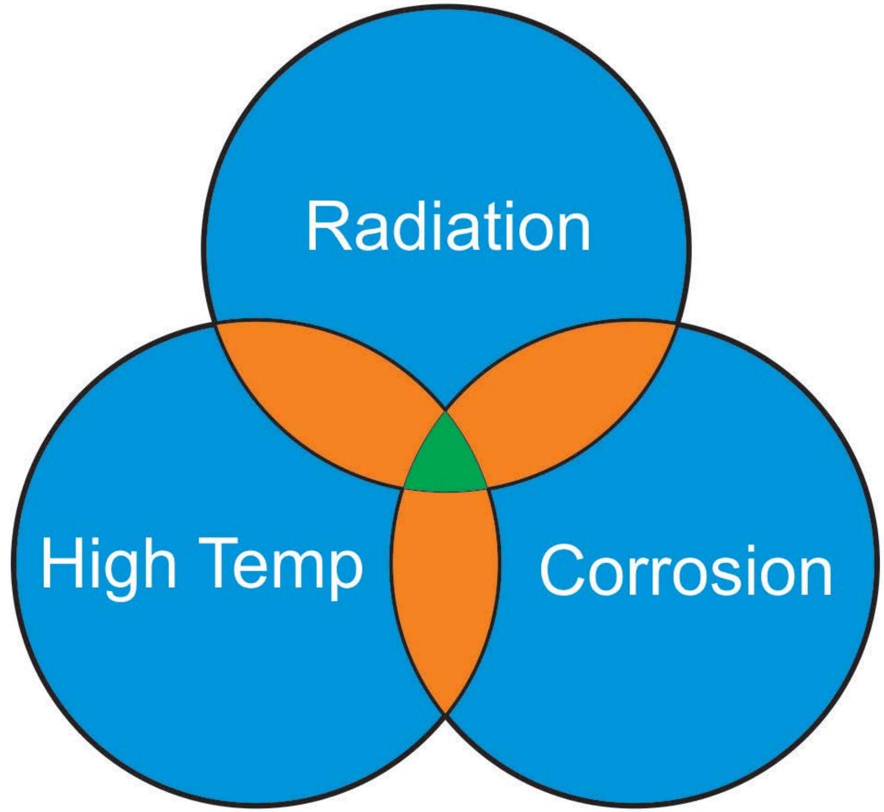
# ANSTO – SINAP Collaboration

- Centre for Thorium Molten Salt Reactor (TMSR) systems
  - Initial $400M R&D investment
  - Non-active Demonstrator

- ANSTO-SINAP Joint Research Centre
  - Materials technology for Molten Salt Reactors
  - Molten salt corrosion
  - Radiation damage
  - High temperature properties

# Generation IV Structural Materials R&D

- Irradiation
  - Neutron, ion damage studies
- High temperature
  - Creep testing
  - Creep/ Fatigue Analysis
- Corrosion
  - Testing in molten salt environments
- Combined environments
  - Irradiation + corrosion (MSR)
  - Corrosion + high temperature creep
  - Irradiation under high temperature

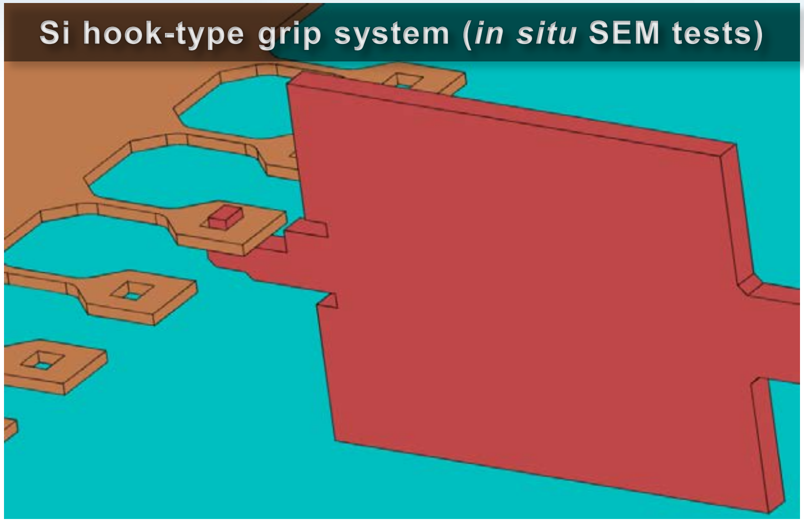


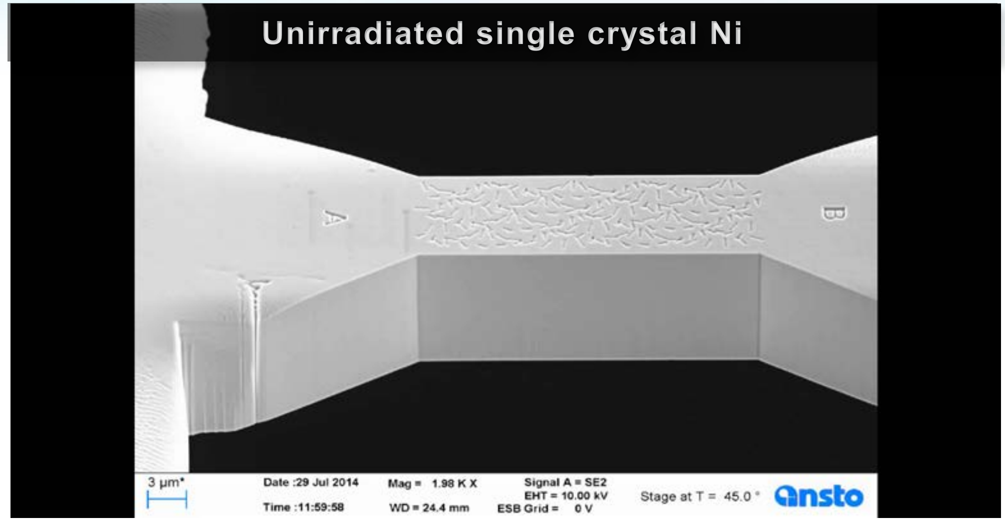

From Lyndon Edwards: Introduction to ANSTO and contributions to GIF with focus on VHTR Materials VHTR SSC 11-12 Nov 2016, Las Vegas, USA

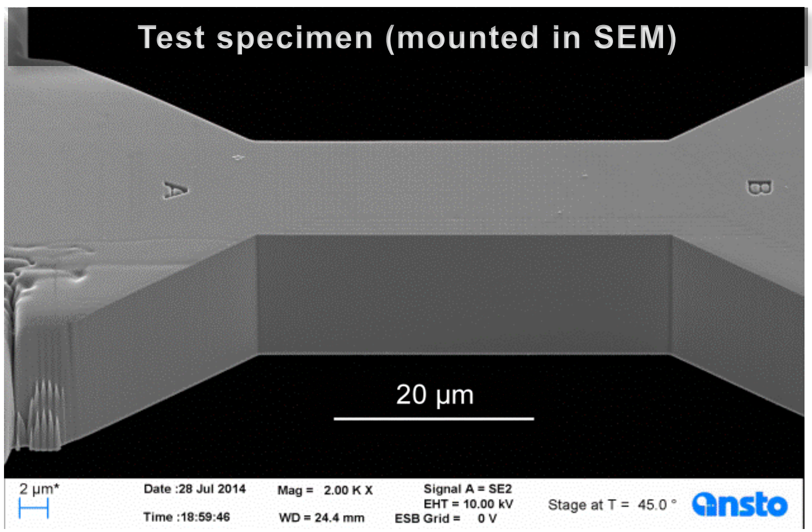
# Requirements of MSR structural materials:

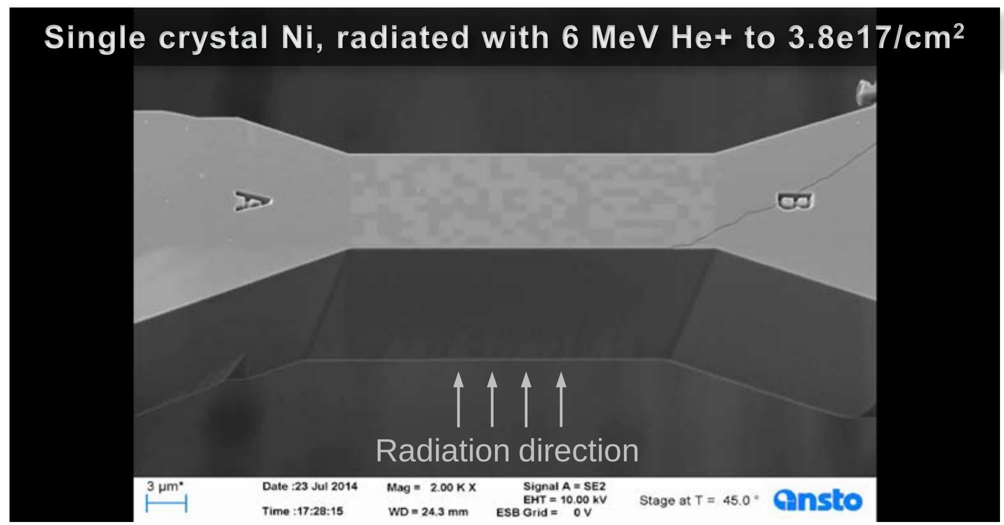
- Operating Temperatures of 630-700$^{o}$C
- Corrosive molten fluoride salt (FLiNaK; FLiBe)
- 200 dpa neutron radiation
- 0.6 MPa pressure
- 30+ years reactor design life

# Micromechanical Tensile Testing



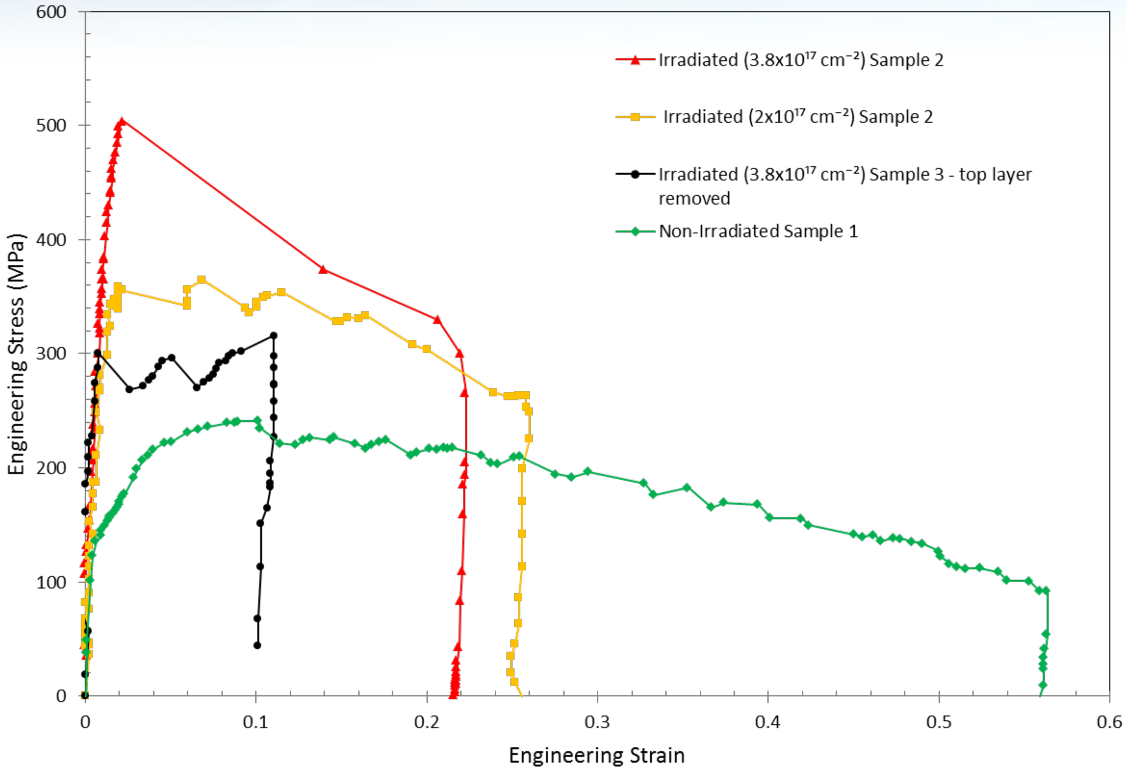



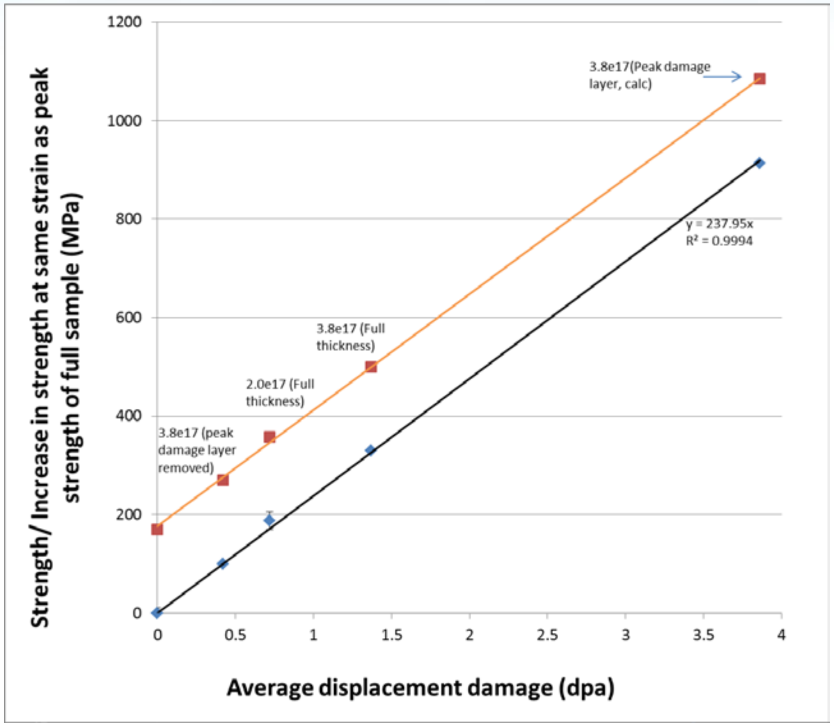




From Lyndon Edwards: Introduction to ANSTO and contributions to GIF with focus on VHTR Materials VHTR SSC 11-12 Nov 2016, Las Vegas, USA

# Trends in Radiation Strengthening with Dose




- Ion irradiation provides useful qualitative information
- Current research linking micro to macro properties

From Lyndon Edwards: Introduction to ANSTO and contributions to GIF with focus on VHTR Materials VHTR SSC 11-12 Nov 2016, Las Vegas, USA

# Effect of Radiation on Strain Rate Response

Engineering stress-strain plot for Nickel single crystal foil

**Unirradiated**

Tested in tension along

a) <100>

b) <110>

orientations at strain rates 5 and 500 n/ps.

Engineering stress-strain plot for Nickel single crystal foil

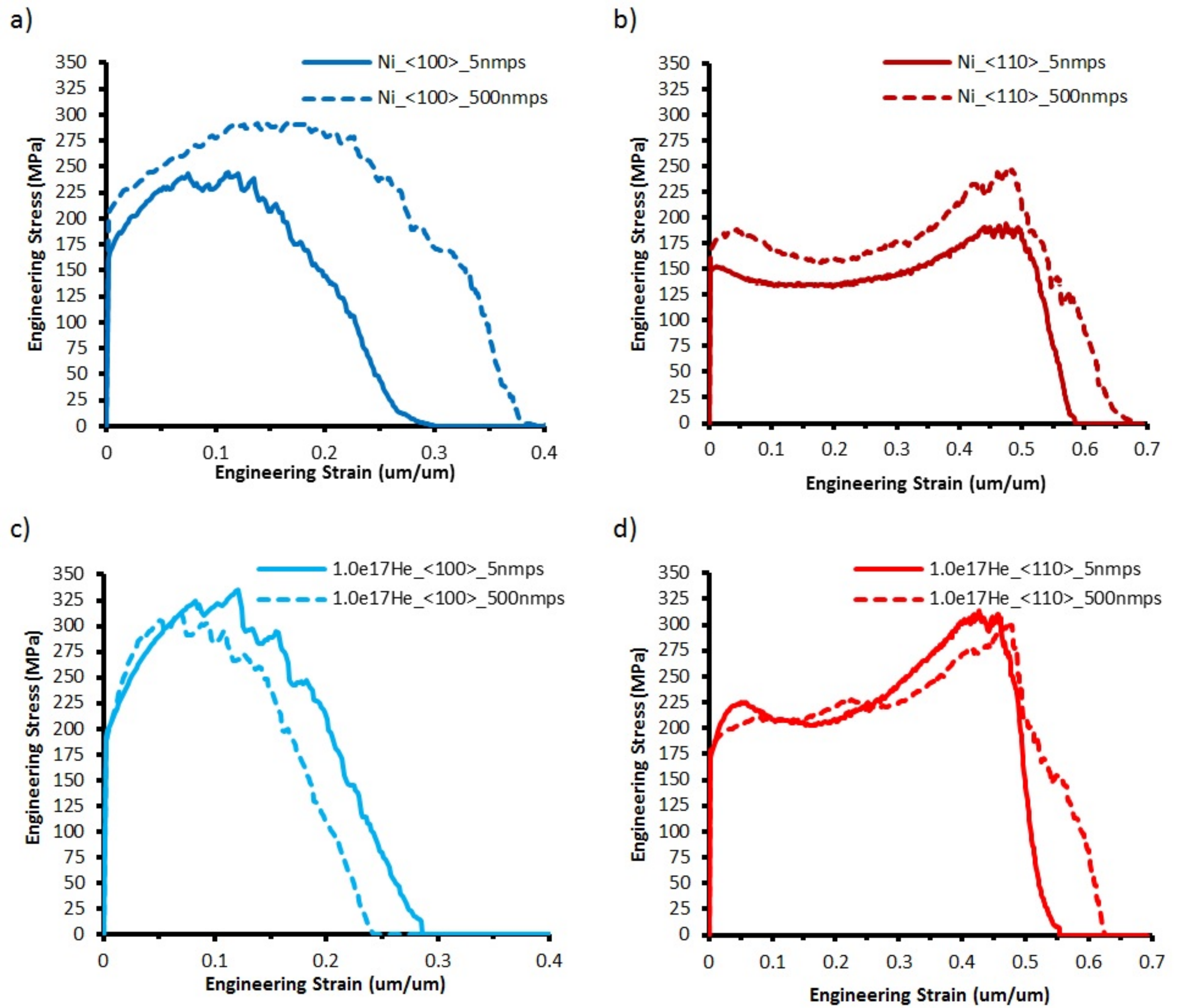
**Irradiated to $10^{17}He^{+}/cm^{2}$**

Tested in tension along

c) <100>

d) <110>

orientations at strain rates 5 and 500 n/ps.

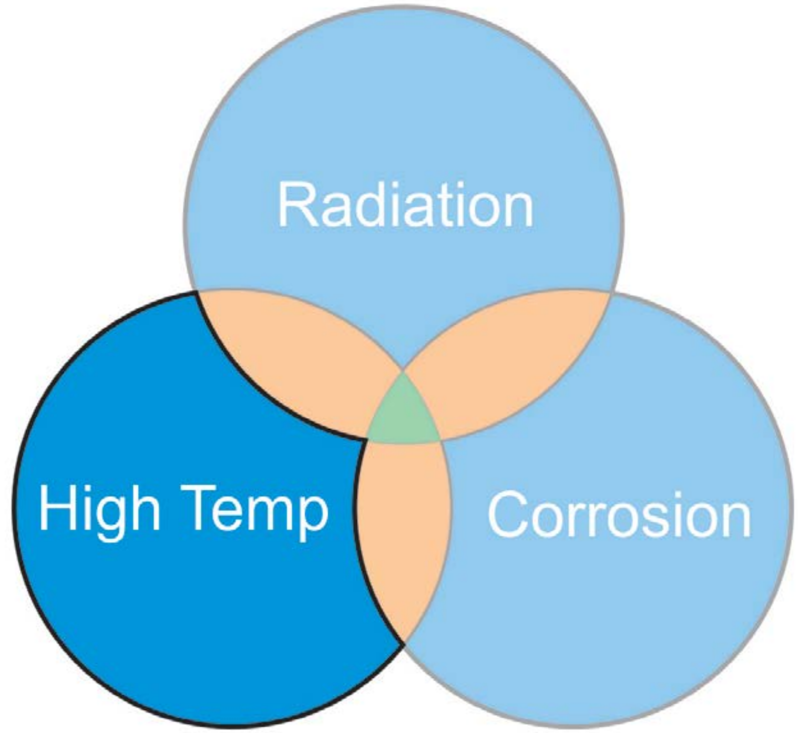



***Xu et. al. unpublished work***

From Lyndon Edwards: Introduction to ANSTO and contributions to GIF with focus on VHTR Materials VHTR SSC 11-12 Nov 2016, Las Vegas, USA

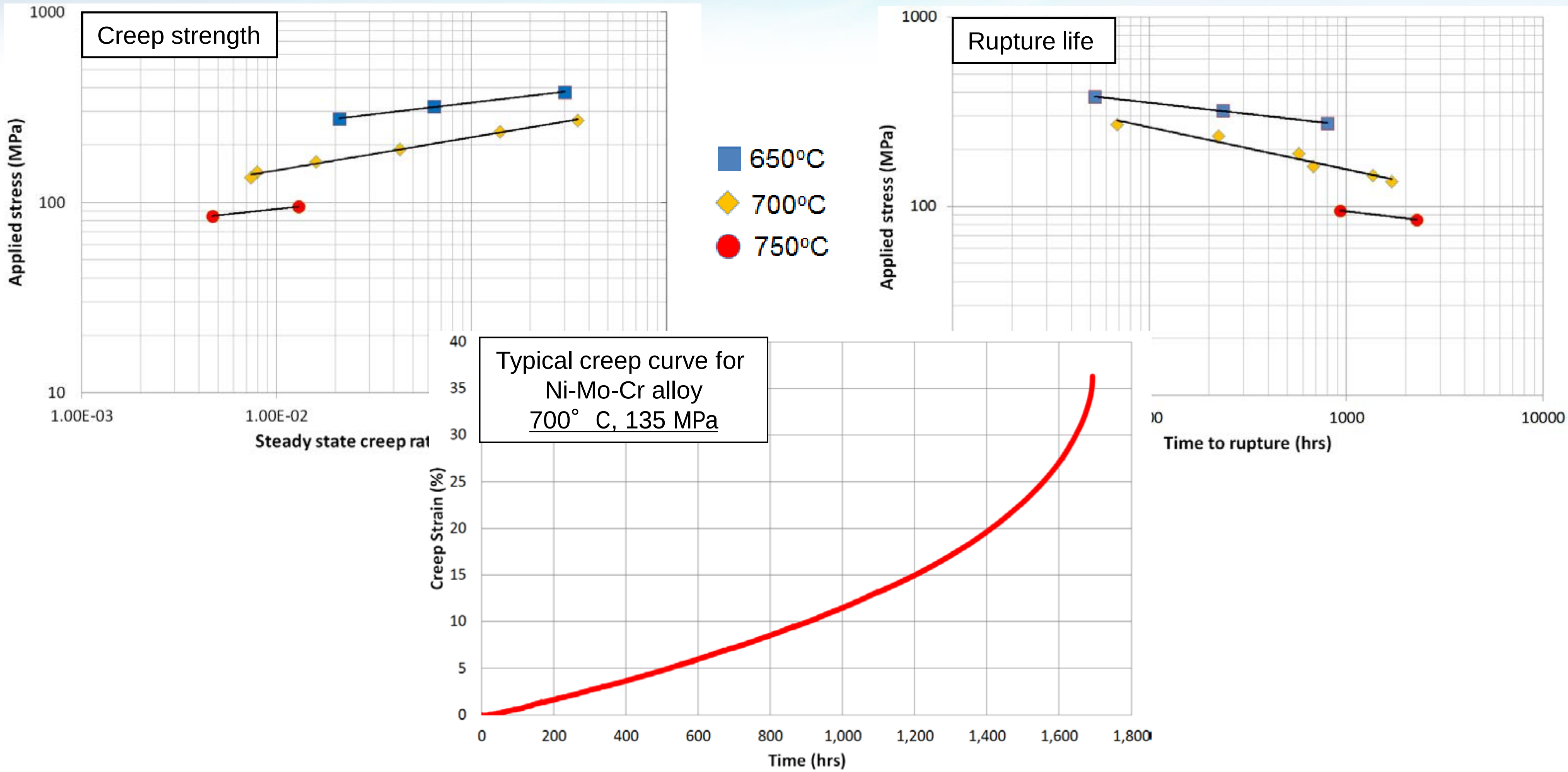
# Gen IV Structural Materials R&D

- Irradiation
  - Neutron, ion damage studies
- High temperature
  - Creep testing
  - Creep/ Fatigue Analysis
- Corrosion
  - Testing in molten salt environments
- Combined environments
  - Irradiation + corrosion (MSR)
  - Corrosion + high temperature
  - Irradiation under high temperature




From Lyndon Edwards: Introduction to ANSTO and contributions to GIF with focus on VHTR Materials VHTR SSC 11-12 Nov 2016, Las Vegas, USA

# MSR - ANSTO/SINAP Creep testing GH3535

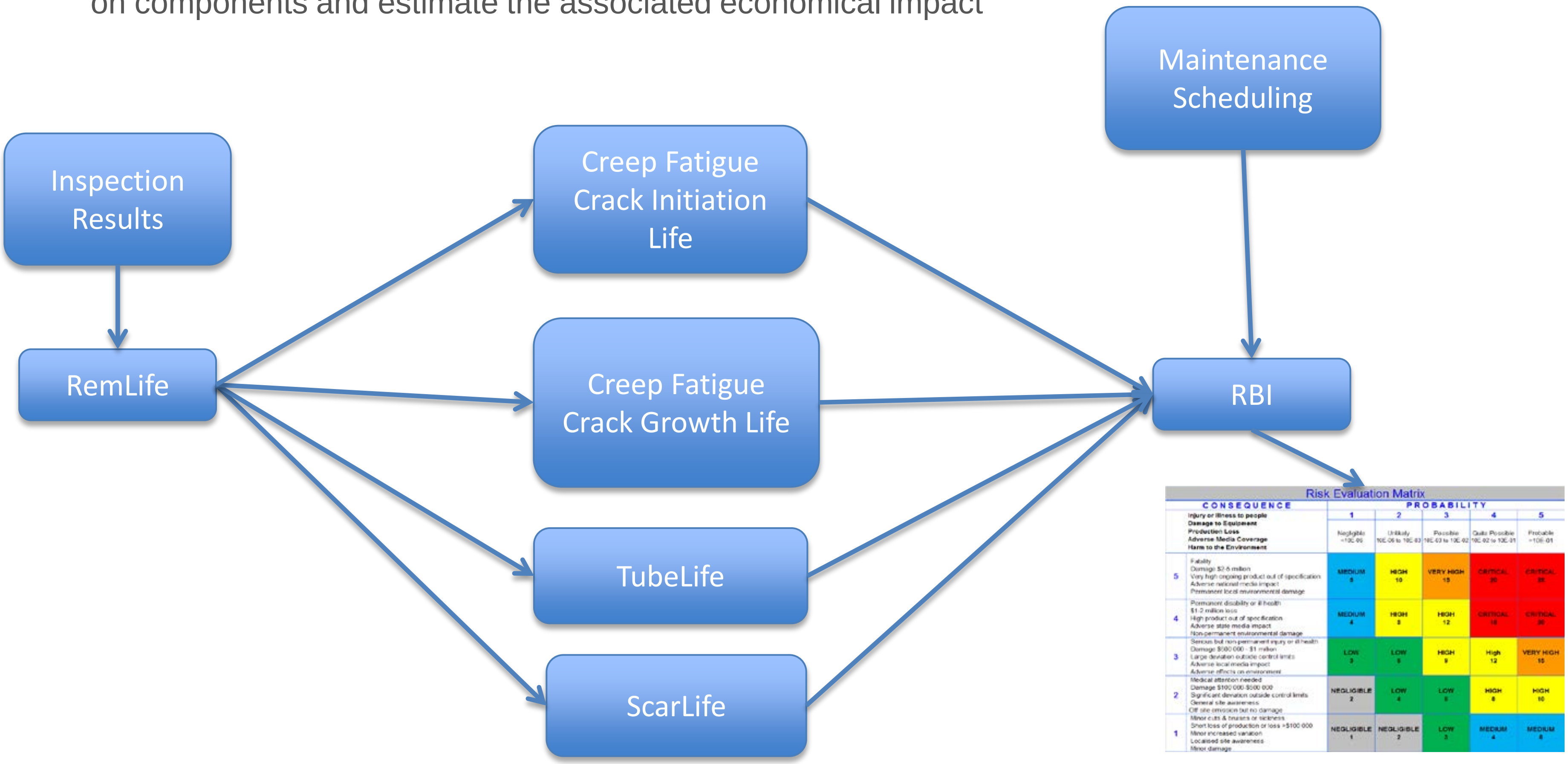



***Creep resistance and material degradation of a candidate Ni-Mo-Cr corrosion resistant alloy. Shrestha et al. Materials Science and Engineering A, 674, pp.64–75***

From Lyndon Edwards: Introduction to ANSTO and contributions to GIF with focus on MSR Related Materials, MSR pSSC 23-24 January PSI, Switzerland, USA

# MSR and VHTR Creep/ Fatigue Analysis

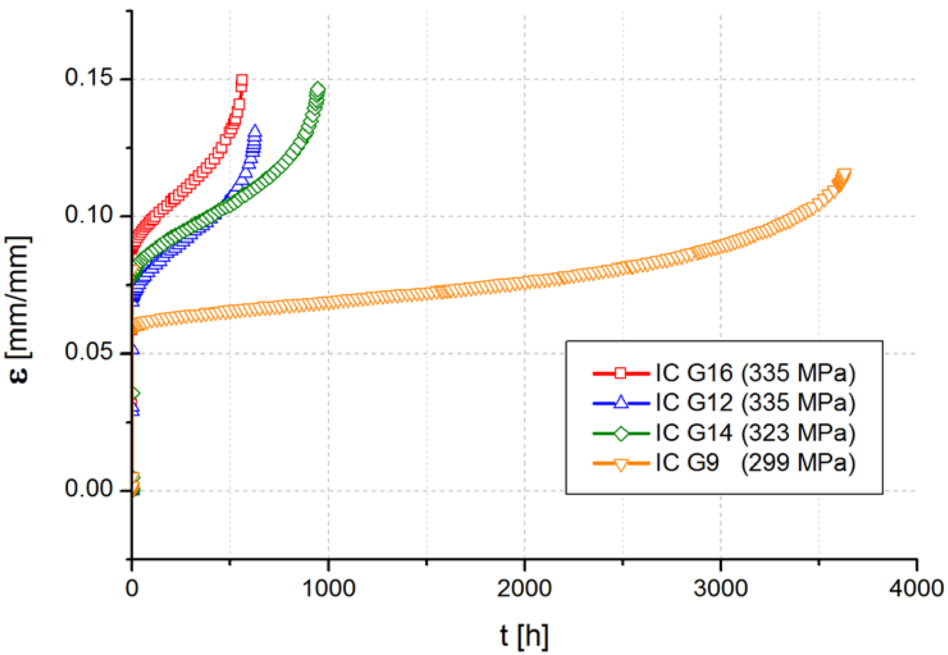
- RemLife Software –
  - Simulator to calculate the effects of unit cycling on the accumulation of creep and creep-fatigue damage on components and estimate the associated economical impact

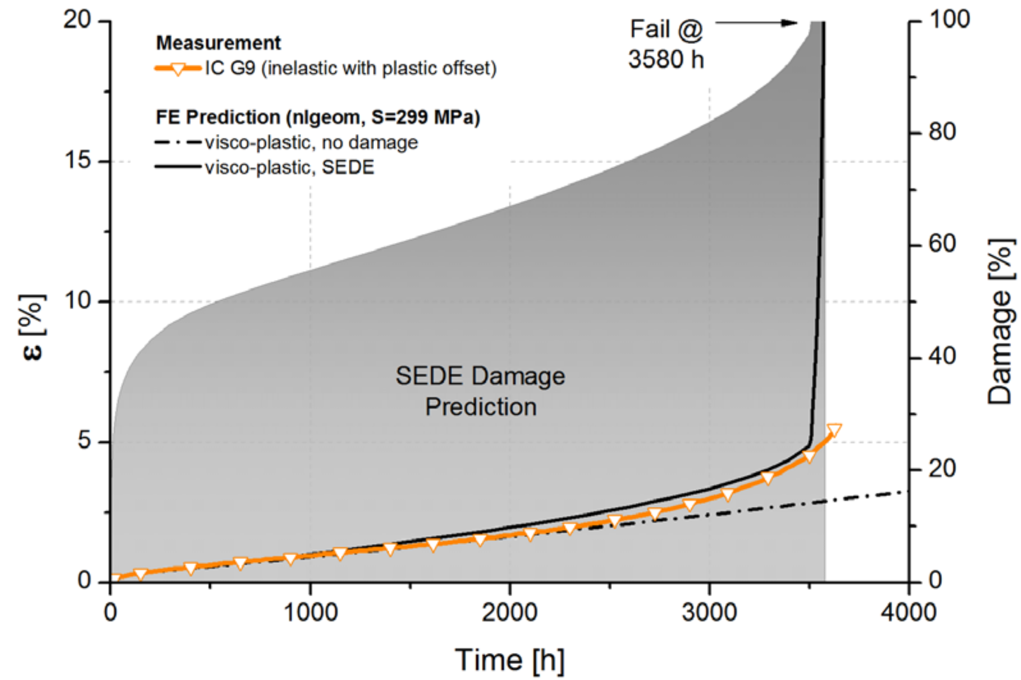



From Lyndon Edwards: Introduction to ANSTO and contributions to GIF with focus on MSR Related Materials, MSR pSSC 23-24 January PSI, Switzerland, USA

# Modelling/Predicting Creep Rupture

- FEA prediction of in-service materials performance
- User-defined material models for creep strain/damage

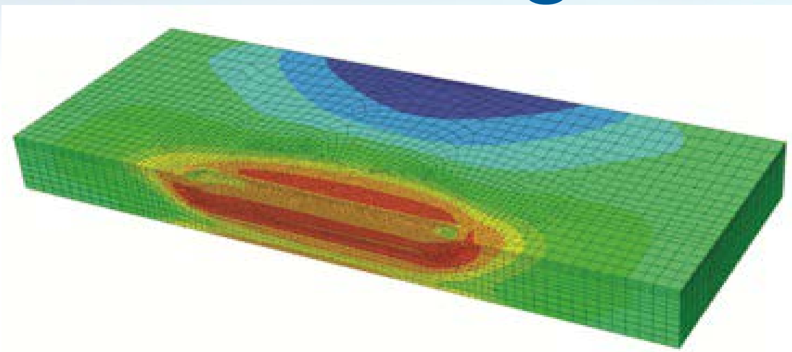


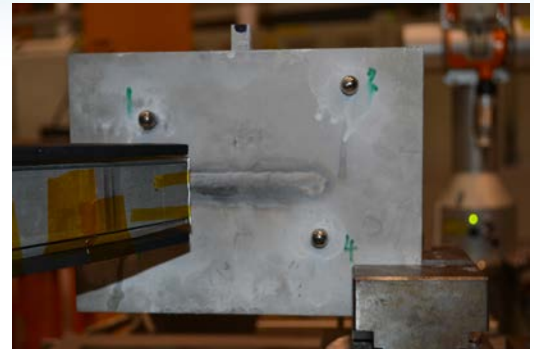




Prediction (via FEA) of creep rupture during an accelerated creep test in ex-service AISI 316H stainless steel using a Strain Energy Ductility Exhaustion (SEDE) creep damage model

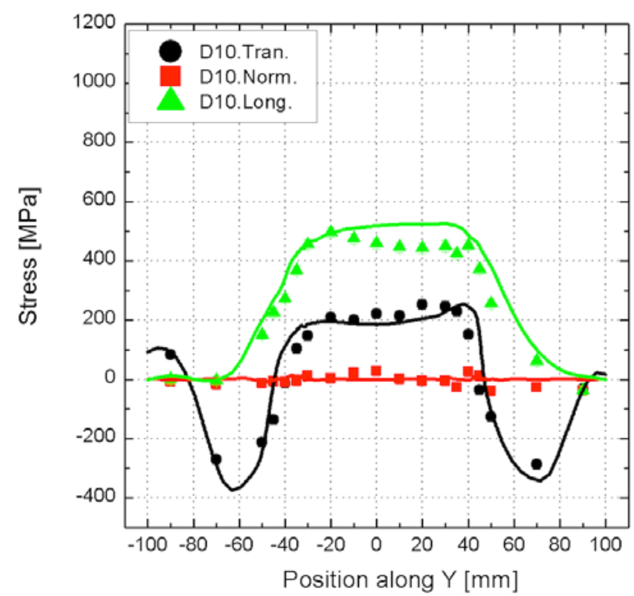
From Lyndon Edwards: Introduction to ANSTO and contributions to GIF with focus on MSR Related Materials, MSR pSSC 23-24 January PSI, Switzerland, USA

# Predicting Weld Residual Stress



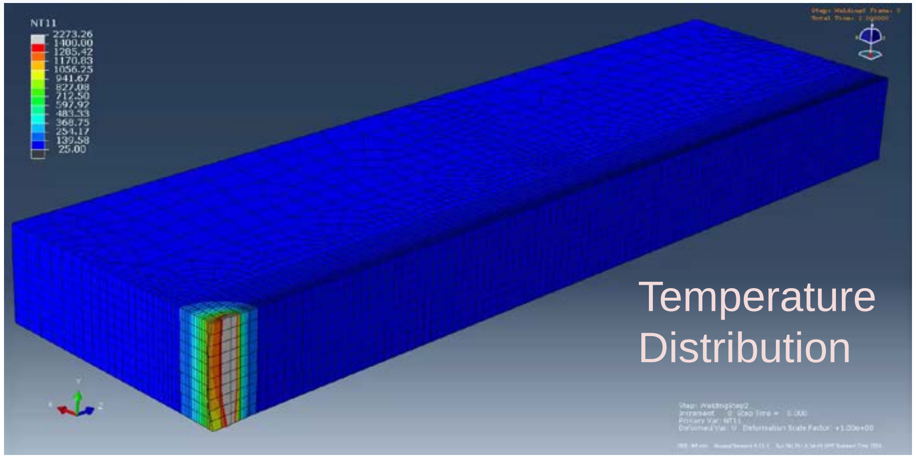


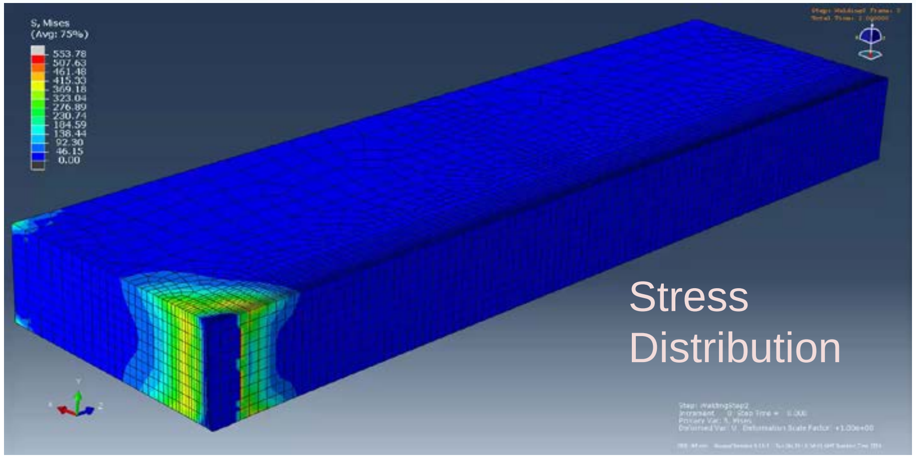
- ANSTO has developed models of microstructure and stress around single- and multi-pass welded joints
- Including international round-robin programmes
  - NeT (AISI 316, Inconel 600, A508)
  - USNRC (DMW)
- Used to support plant maintenance and design decisions

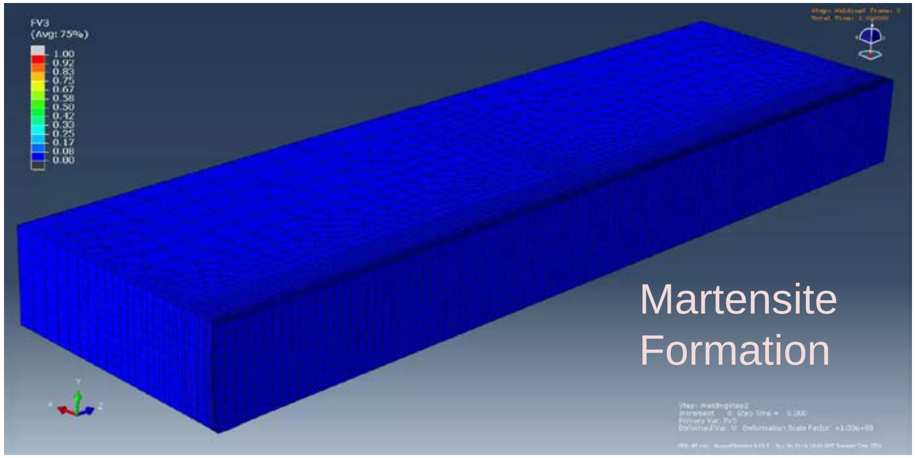


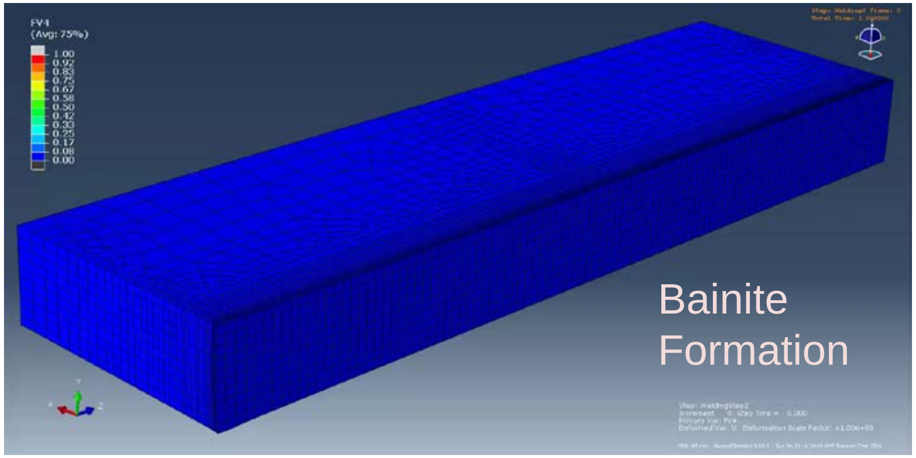

From Lyndon Edwards: Introduction to ANSTO and contributions to GIF with focus on VHTR Materials VHTR SSC 11-12 Nov 2016, Las Vegas, USA

# Typical Weld Simulation: A 508 EB Weld




Courtesy A. Vasileiou, University of Manchester

From Lyndon Edwards: Introduction to ANSTO and contributions to GIF with focus on VHTR Materials VHTR SSC 11-12 Nov 2016, Las Vegas, USA

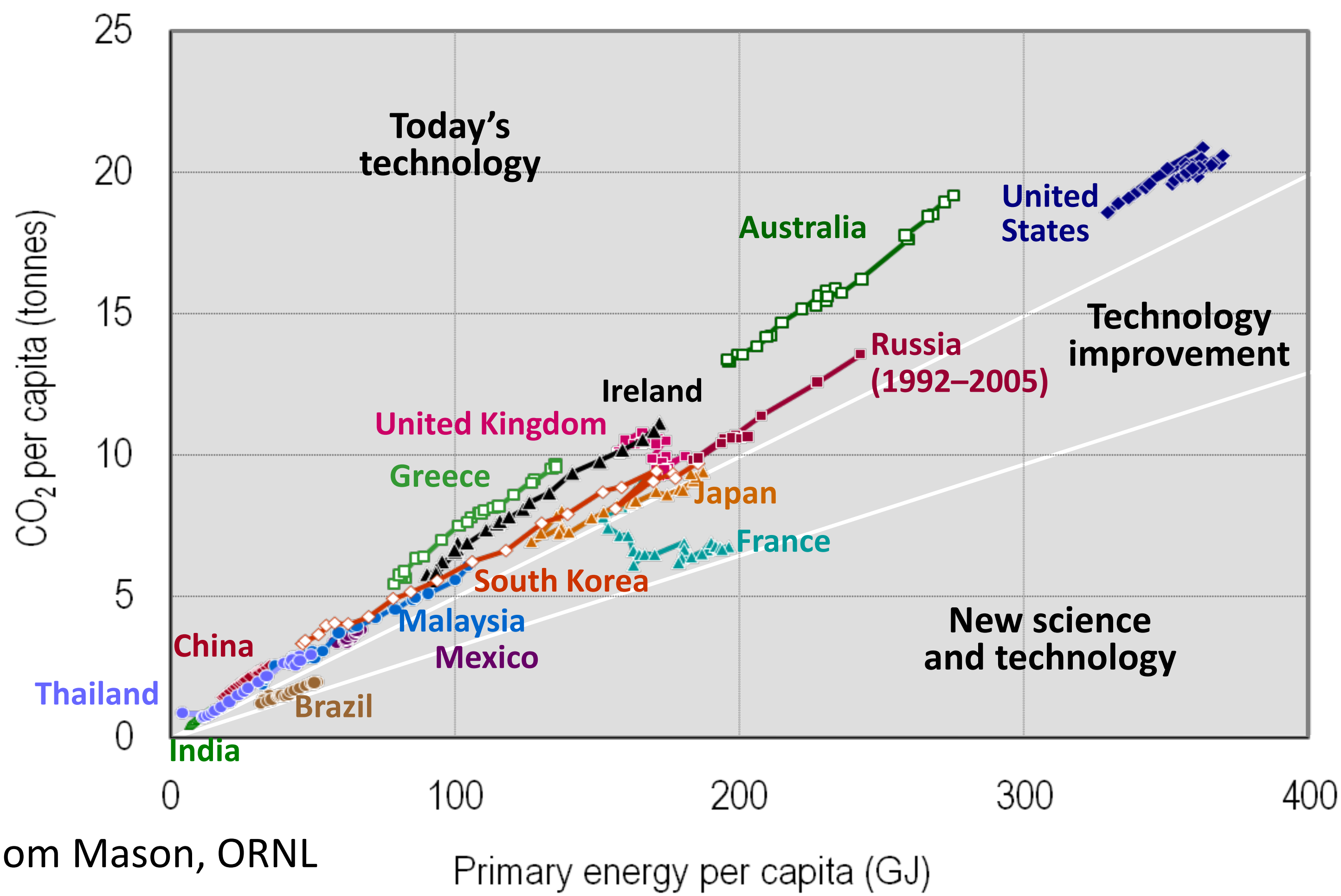
# 2020s Nuclear Value Proposition

- Baseload
- Low-carbon
- Low fuel cost
- Extended Plant Life
- Safer
- Replaces Coal
- Could replace Gas and Oil
- But…………….

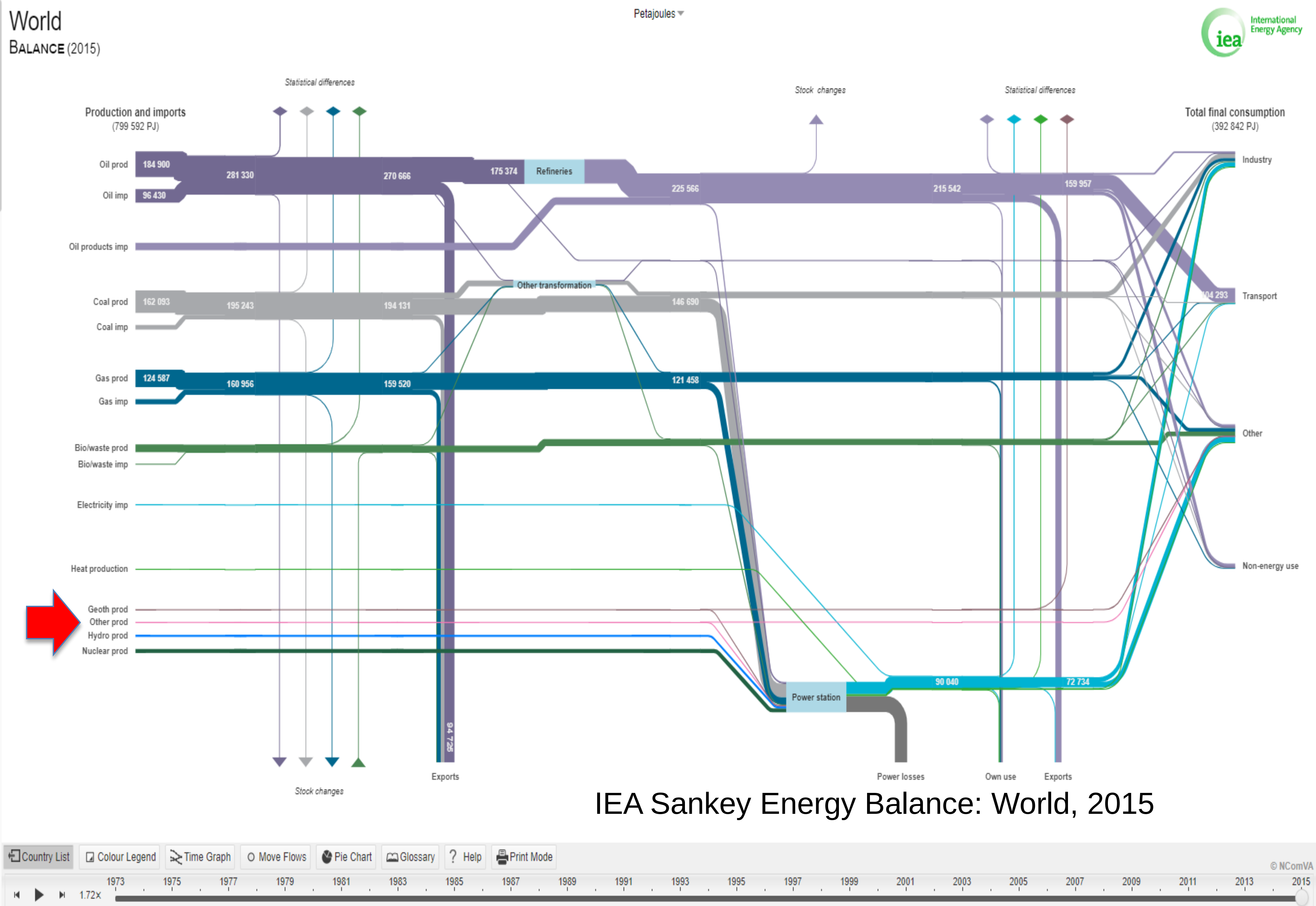
# But……….

- Do we understand anything about the energy state of the planet?
- And electricity is only a small part of this!

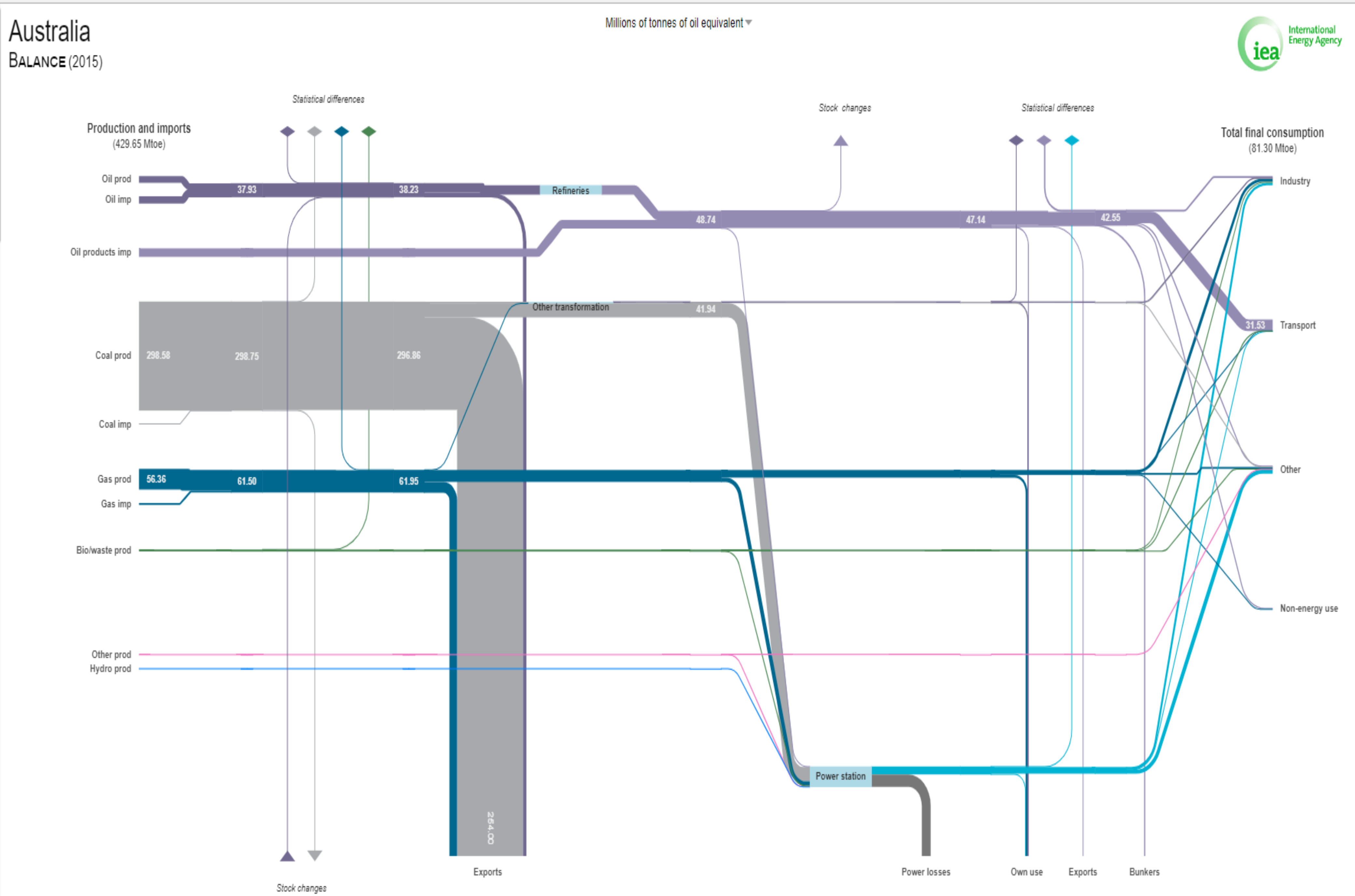
# Breaking the link
# Energy and $CO_2$ emissions




Source: Thom Mason, ORNL

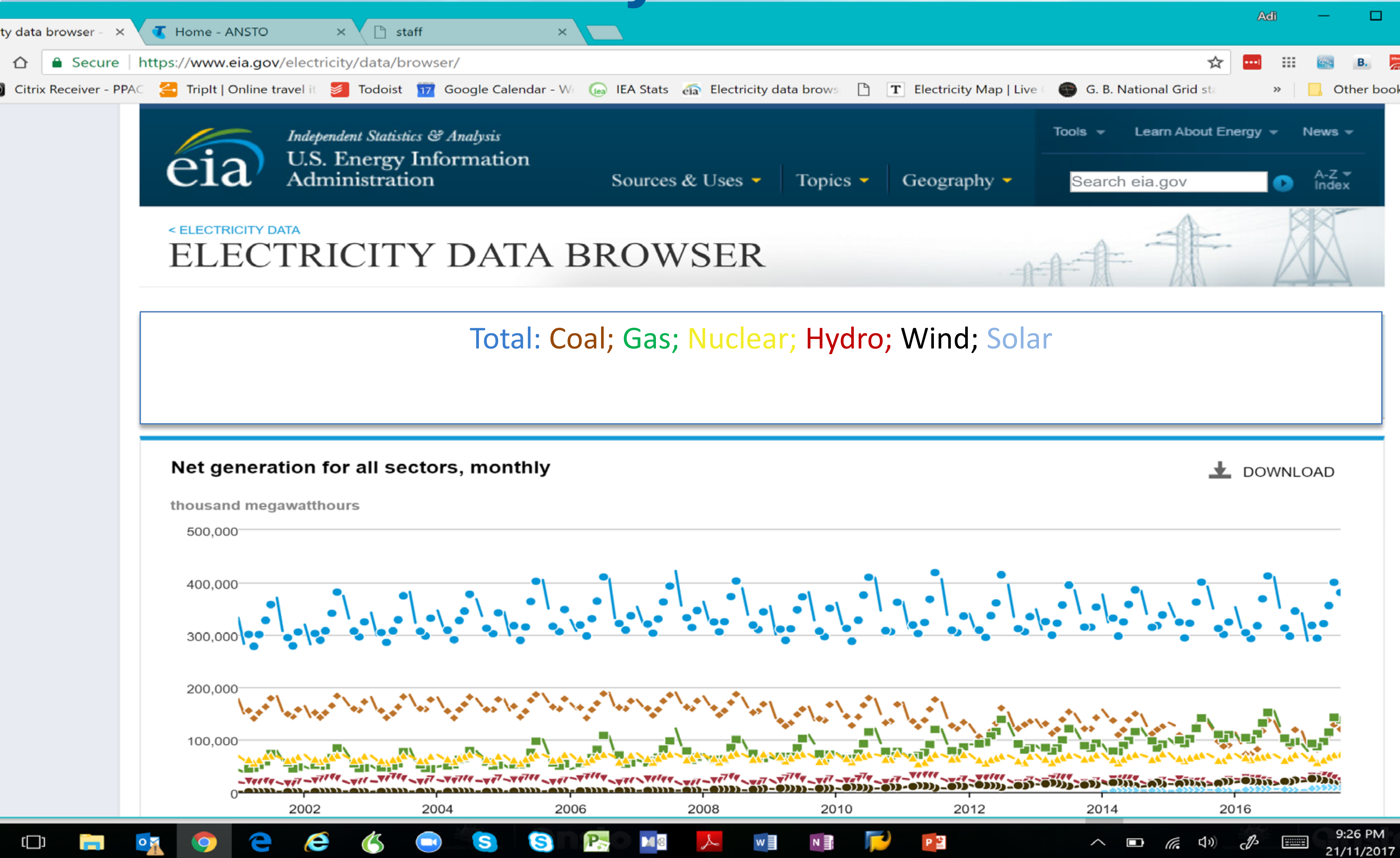



IEA Sankey Energy Balance: World, 2015

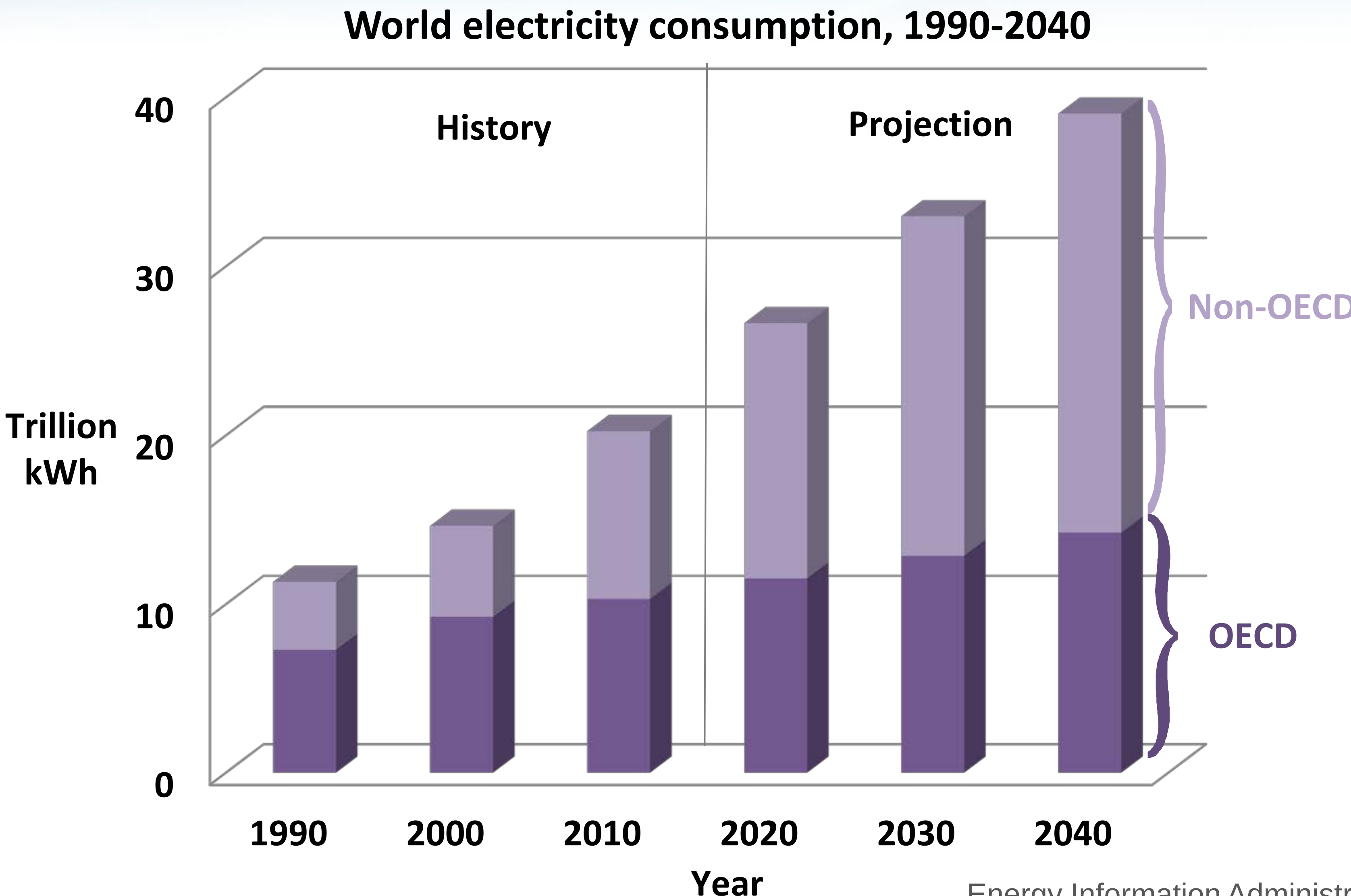



IEA Sankey Energy Balance: Australia, 2015

# USA Electricity Data 2002 to 2017

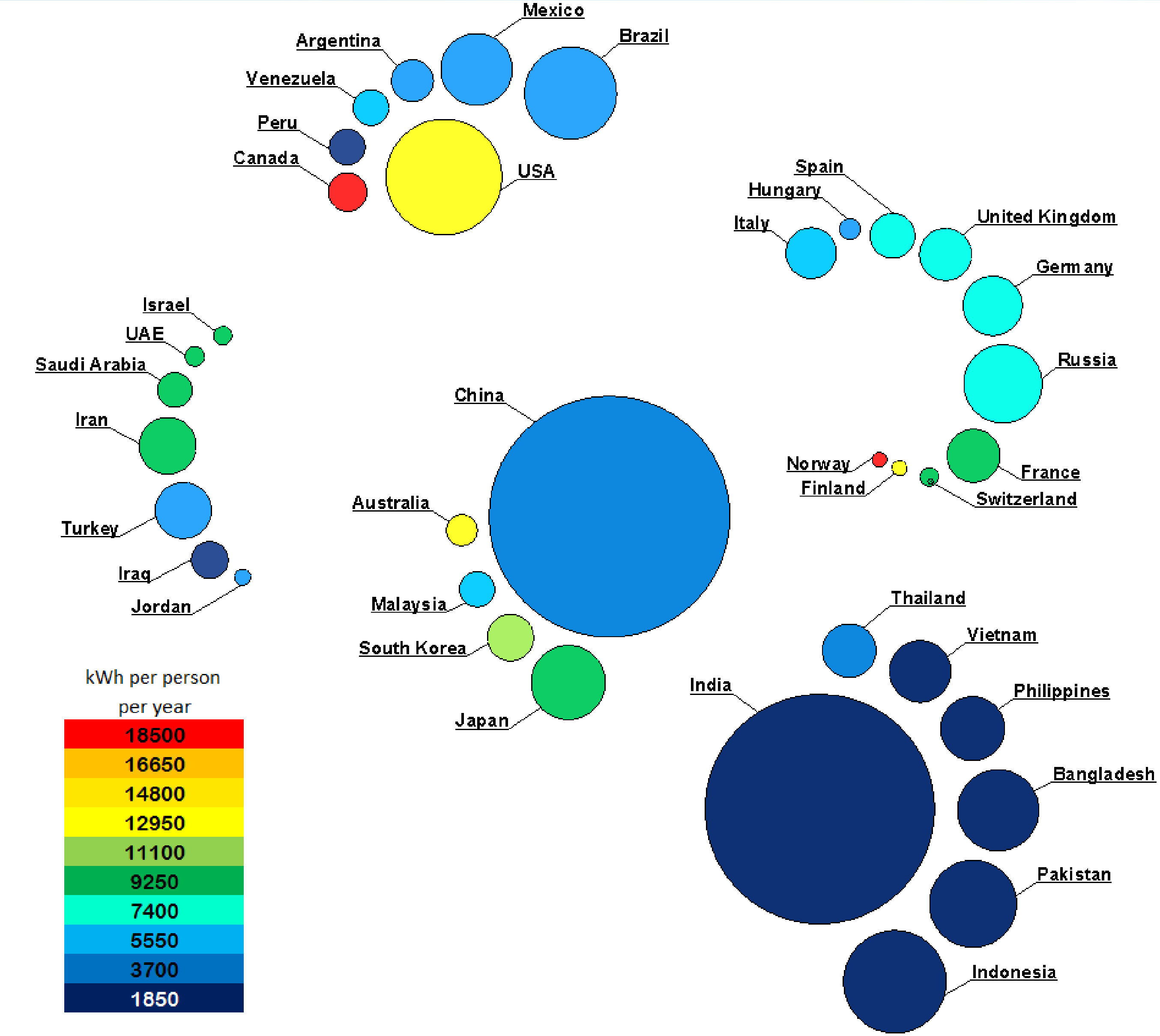


# Energy growth in non-OECD nations




Energy Information Administration, USA.

# Electricity use per capita: asymmetrical..




Source: World Bank, 2011
Graphic: Mark Ho

# Australia in global perspective

- Problem: confusing electricity with energy!
- Solution: Clean **energy** consensus

- Problem: ignoring emerging economies
- Solution: Global perspective essential

- Problem: $CO_2$
- Solution: Clean Fuels

- Option: Nuclear
- Solution: SMR, then GEN IV

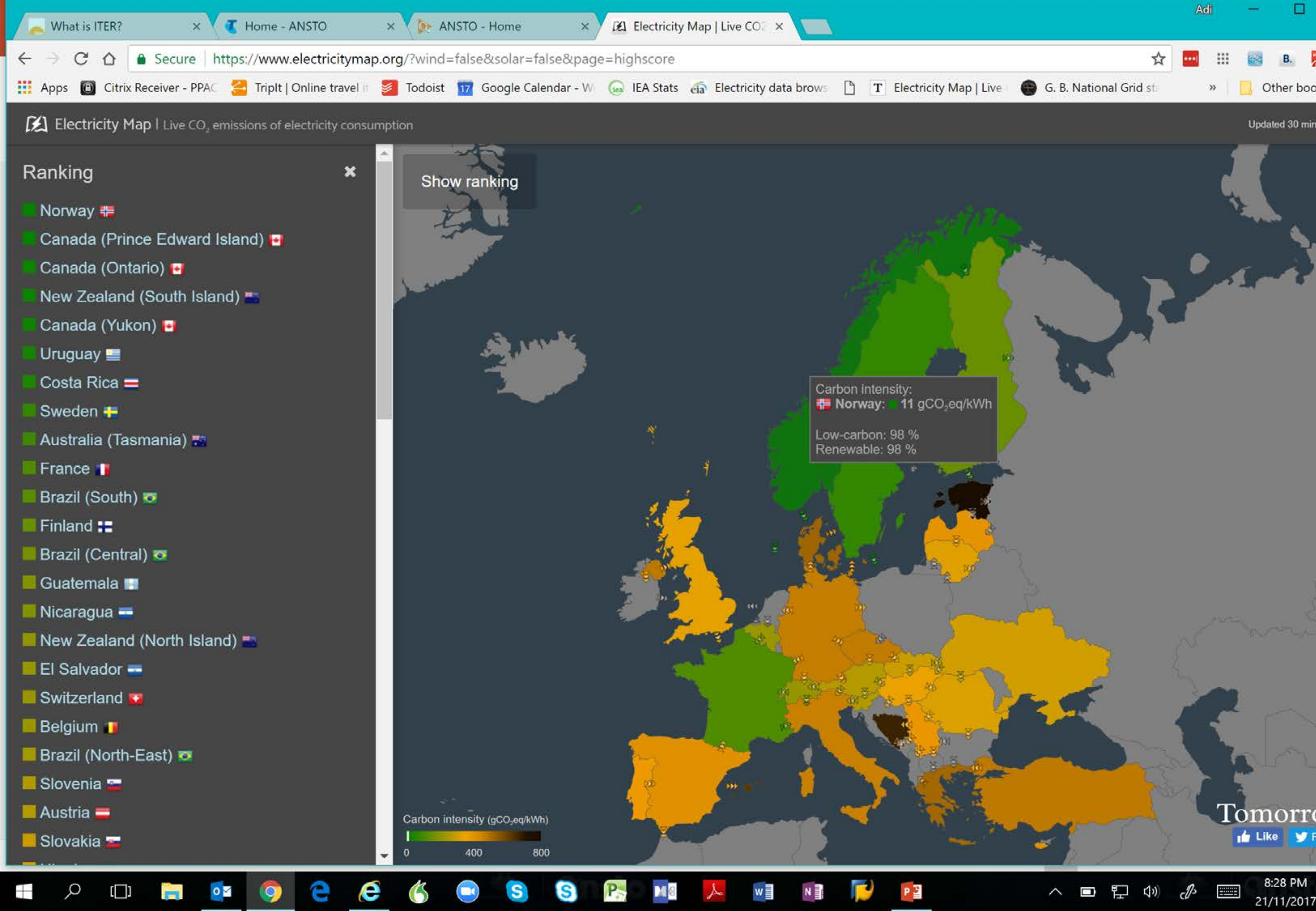

ANSTO  making sense of nuclear

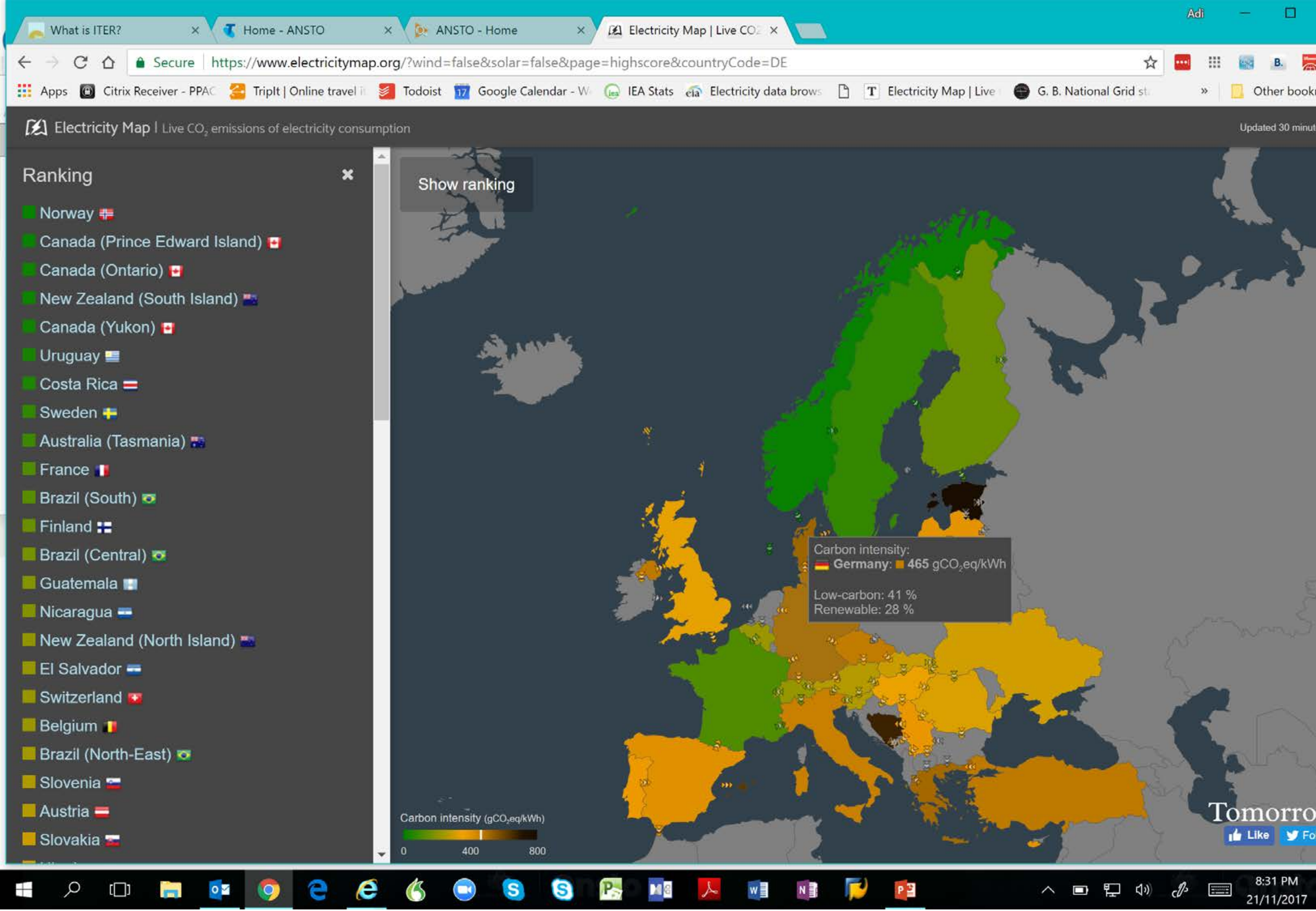
# Thank You

# Carbon Intensity Notes

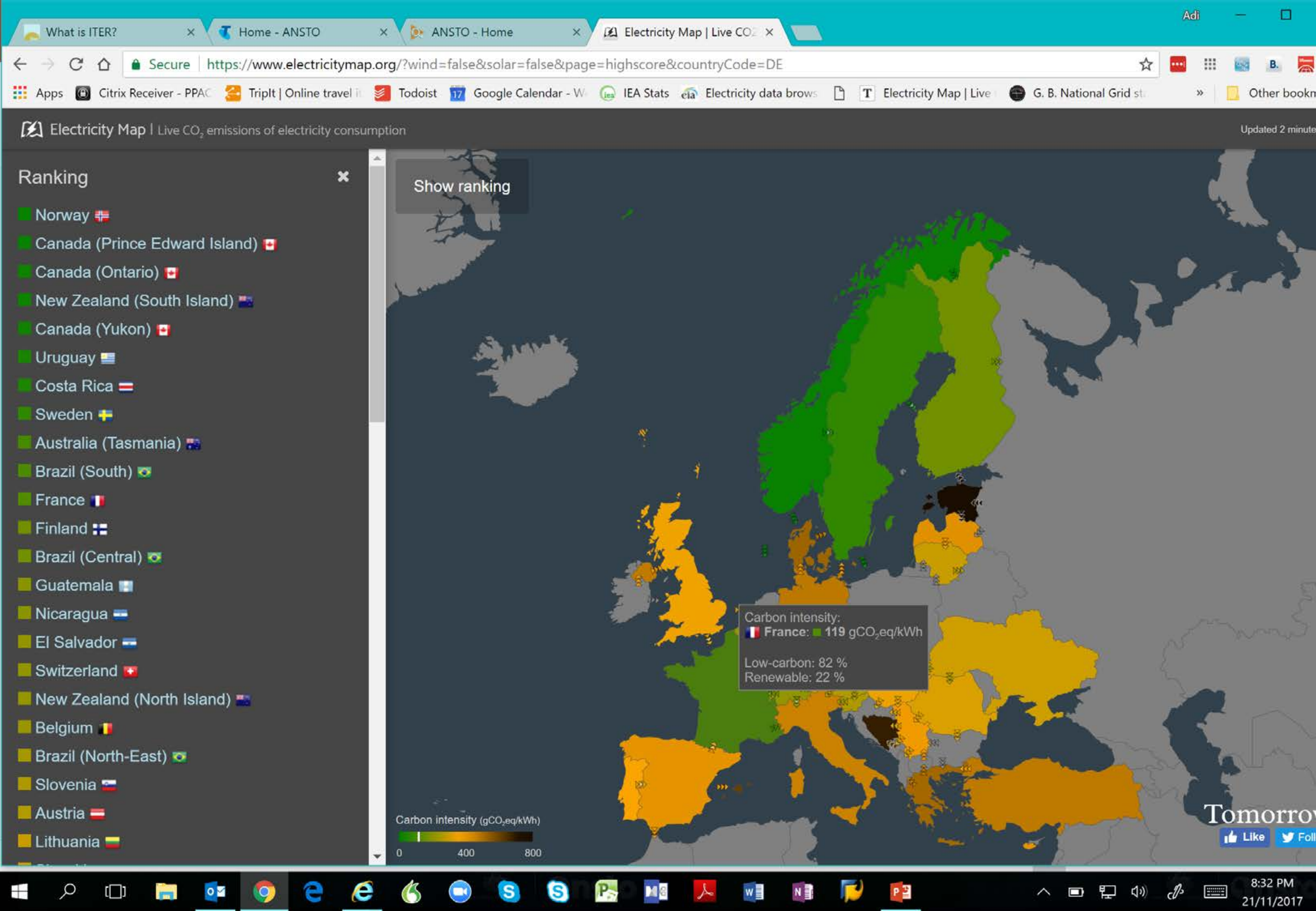
- Electricitymap.org
- 21/11/17 AEDT
- From about  8:30pm

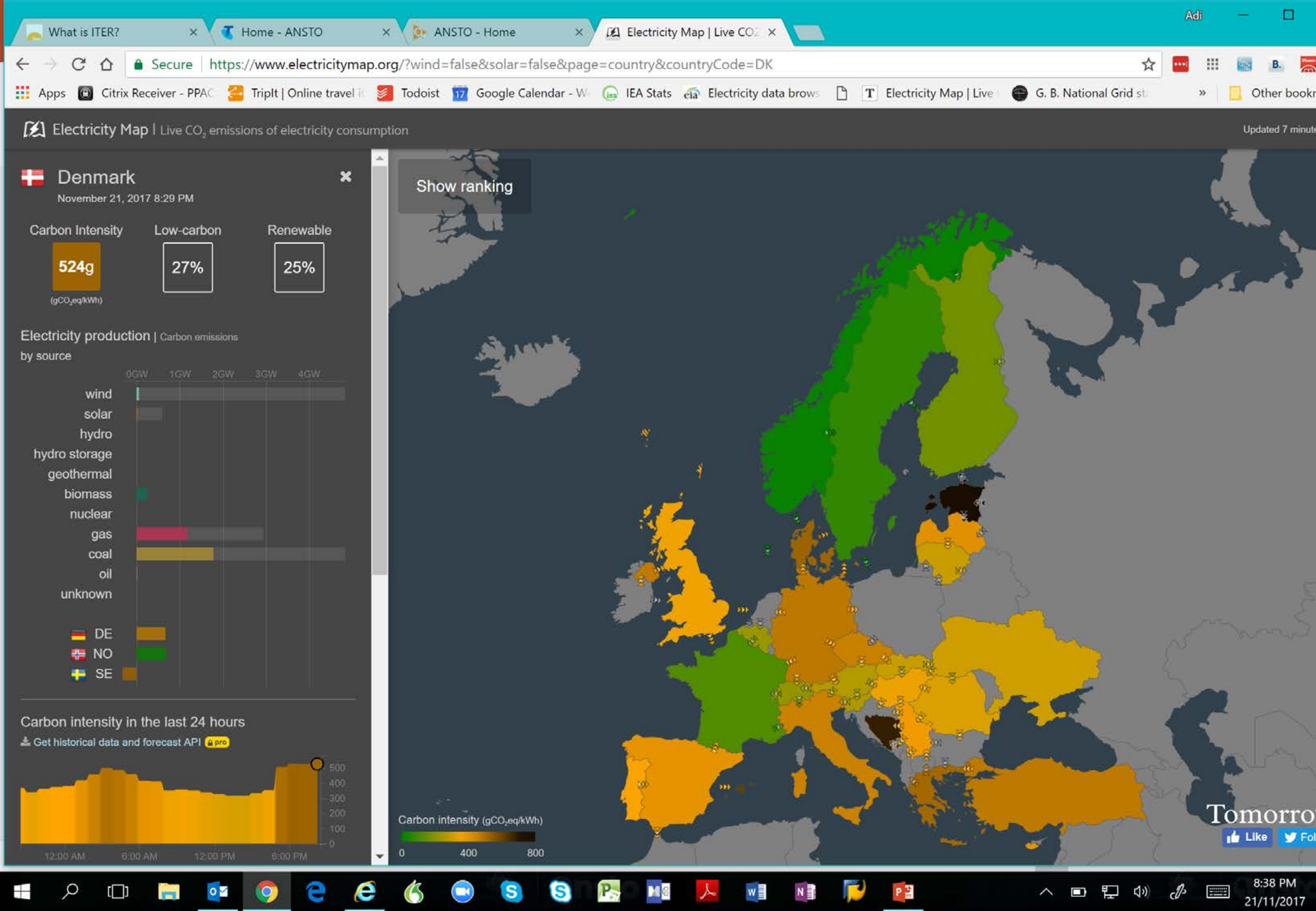
- Nuclear and Hydro lead the charge!

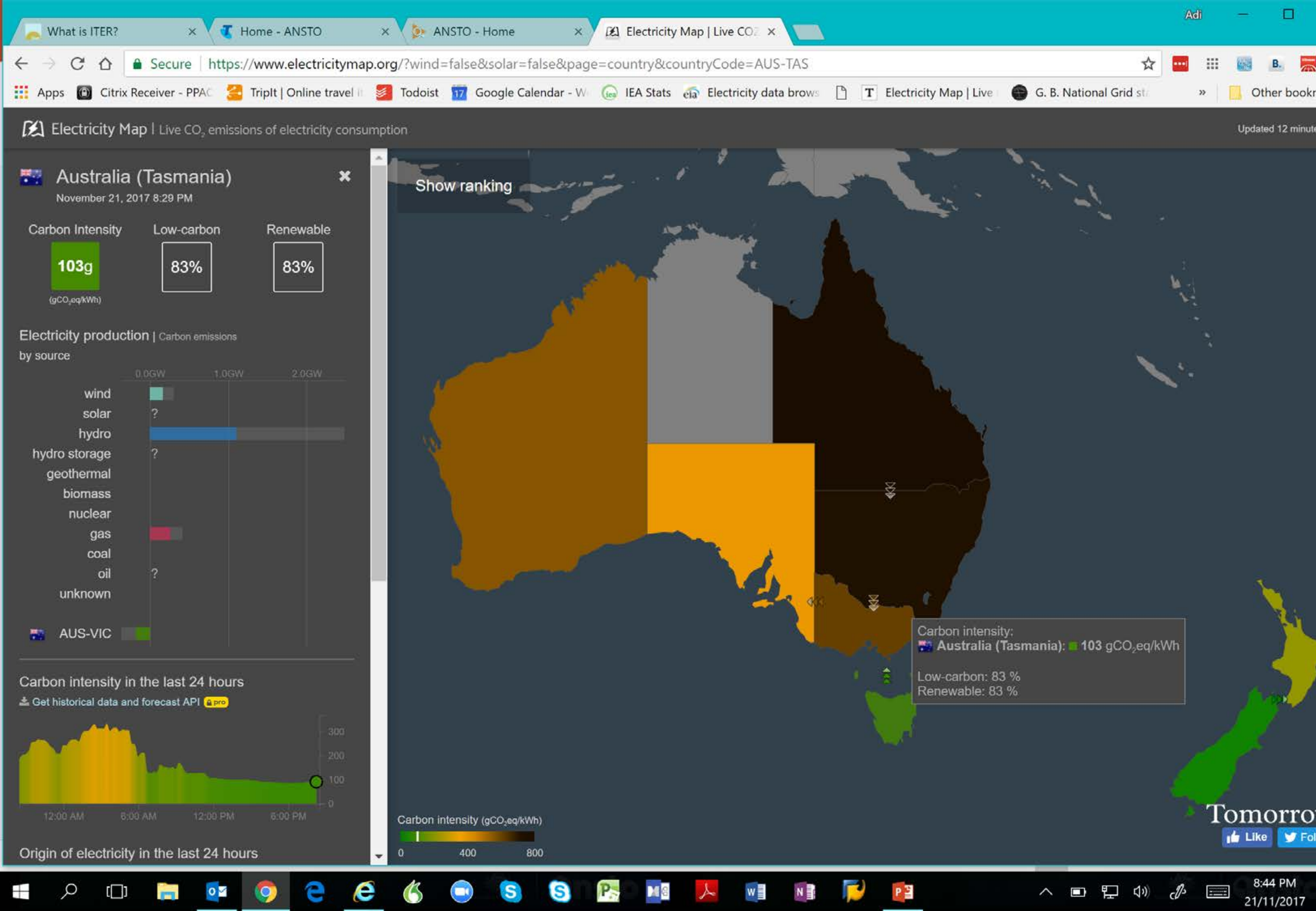

What is ITER?
Home - ANSTO
ANSTO - Home
Electricity Map | Live CO2
Secure
https://www.electricitymap.org/?wind=false&solar=false&page=highscore
Apps
Citrix Receiver - PPAC
TripIt | Online travel
Todoist
Google Calendar - W
IEA Stats
Electricity data brows
Electricity Map | Live
G. B. National Grid st
Other boo
Electricity Map | Live CO2 emissions of electricity consumption
Updated 30 min
Ranking
Norway
Canada (Prince Edward Island)
Canada (Ontario)
New Zealand (South Island)
Canada (Yukon)
Uruguay
Costa Rica
Sweden
Australia (Tasmania)
France
Brazil (South)
Finland
Brazil (Central)
Guatemala
Nicaragua
New Zealand (North Island)
El Salvador
Switzerland
Belgium
Brazil (North-East)
Slovenia
Austria
Slovakia
Show ranking
Carbon intensity:
Norway: 11 gCO2eq/kWh
Low-carbon: 98 %
Renewable: 98 %
Carbon intensity (gCO2eq/kWh)
0
400
800
Tomorro
Like
8:28 PM
21/11/2017

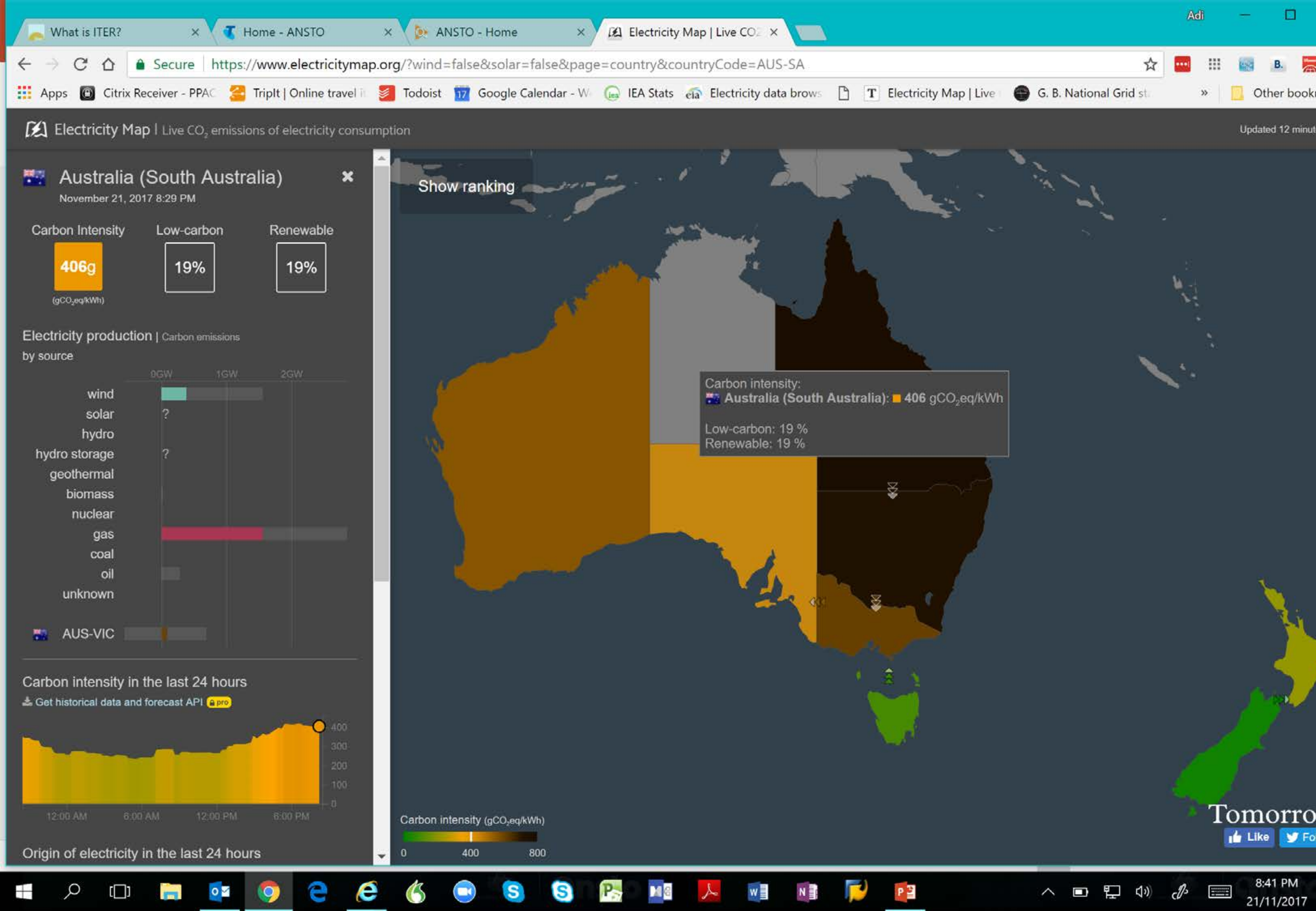


What is ITER?
Home - ANSTO
ANSTO - Home
Electricity Map | Live CO2
Secure
https://www.electricitymap.org/?wind=false&solar=false&page=highscore&countryCode=DE
Apps
Citrix Receiver - PPAC
TripIt | Online travel
Todoist
Google Calendar - W
IEA Stats
Electricity data brows
Electricity Map | Live
G. B. National Grid st
Other book
Electricity Map | Live CO2 emissions of electricity consumption
Updated 30 minut
Ranking
Norway
Canada (Prince Edward Island)
Canada (Ontario)
New Zealand (South Island)
Canada (Yukon)
Uruguay
Costa Rica
Sweden
Australia (Tasmania)
France
Brazil (South)
Finland
Brazil (Central)
Guatemala
Nicaragua
New Zealand (North Island)
El Salvador
Switzerland
Belgium
Brazil (North-East)
Slovenia
Austria
Slovakia
Show ranking
Carbon intensity:
Germany: 465 gCO2eq/kWh
Low-carbon: 41 %
Renewable: 28 %
Carbon intensity (gCO2eq/kWh)
0
400
800
Tomorro
Like
8:31 PM
21/11/2017

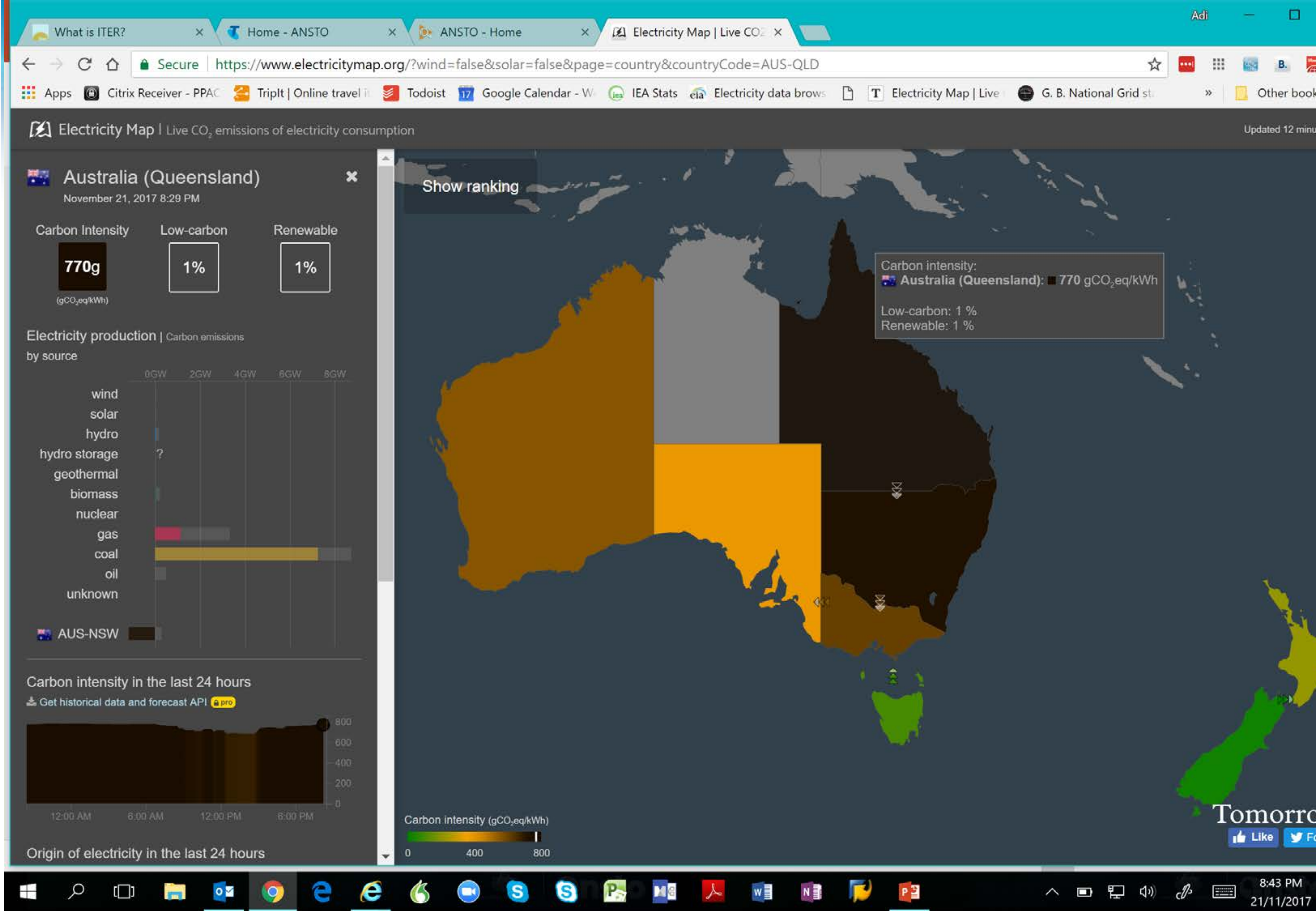

What is ITER?
Home - ANSTO
ANSTO - Home
Electricity Map | Live CO
https://www.electricitymap.org/?wind=false&solar=false&page=highscore&countryCode=DE
Electricity Map | Live CO2 emissions of electricity consumption
Ranking
Norway
Canada (Prince Edward Island)
Canada (Ontario)
New Zealand (South Island)
Canada (Yukon)
Uruguay
Costa Rica
Sweden
Australia (Tasmania)
Brazil (South)
France
Finland
Brazil (Central)
Guatemala
Nicaragua
El Salvador
Switzerland
New Zealand (North Island)
Belgium
Brazil (North-East)
Slovenia
Austria
Lithuania
Show ranking
Carbon intensity:
France: 119 gCO2eq/kWh
Low-carbon: 82 %
Renewable: 22 %
Carbon intensity (gCO2eq/kWh)
0
400
800
8:32 PM
21/11/2017


What is ITER?
Home - ANSTO
ANSTO - Home
Electricity Map | Live CO2
Secure
https://www.electricitymap.org/?wind=false&solar=false&page=country&countryCode=DK
Apps
Citrix Receiver - PPAC
TripIt | Online travel
Todoist
Google Calendar - W
IEA Stats
Electricity data brows
Electricity Map | Live
G. B. National Grid st
Other bookr
Electricity Map | Live CO2 emissions of electricity consumption
Updated 7 minut
Denmark
November 21, 2017 8:29 PM
Carbon Intensity
524g
(gCO2eq/kWh)
Low-carbon
27%
Renewable
25%
Electricity production | Carbon emissions
by source
0GW
1GW
2GW
3GW
4GW
wind
solar
hydro
hydro storage
geothermal
biomass
nuclear
gas
coal
oil
unknown
DE
NO
SE
Carbon intensity in the last 24 hours
Get historical data and forecast API
pro
500
400
300
200
100
0
12:00 AM
6:00 AM
12:00 PM
6:00 PM
Show ranking
Carbon intensity (gCO2eq/kWh)
0
400
800
Tomorro
Like
Fol
8:38 PM
21/11/2017


What is ITER?
Home - ANSTO
ANSTO - Home
Electricity Map | Live CO2
Secure
https://www.electricitymap.org/?wind=false&solar=false&page=country&countryCode=AUS-TAS
Apps
Citrix Receiver - PPAC
TripIt | Online travel
Todoist
Google Calendar
IEA Stats
Electricity data brows
Electricity Map | Live
G. B. National Grid st
Other book
Electricity Map | Live CO2 emissions of electricity consumption
Show ranking
Australia (Tasmania)
November 21, 2017 8:29 PM
Carbon Intensity
Low-carbon
Renewable
103g
83%
83%
(gCO2eq/kWh)
Electricity production | Carbon emissions
by source
0.0GW
1.0GW
2.0GW
wind
solar
hydro
hydro storage
geothermal
biomass
nuclear
gas
coal
oil
unknown
AUS-VIC
Carbon intensity in the last 24 hours
Get historical data and forecast API
pro
300
200
100
0
12:00 AM
6:00 AM
12:00 PM
6:00 PM
Origin of electricity in the last 24 hours
Carbon intensity:
Australia (Tasmania): 103 gCO2eq/kWh
Low-carbon: 83 %
Renewable: 83 %
Carbon intensity (gCO2eq/kWh)
0
400
800
Like
8:44 PM
21/11/2017



What is ITER?
Home - ANSTO
ANSTO - Home
Electricity Map | Live CO2
https://www.electricitymap.org/?wind=false&solar=false&page=country&countryCode=AUS-SA
Electricity Map | Live CO2 emissions of electricity consumption
Australia (South Australia)
November 21, 2017 8:29 PM
Carbon Intensity
406g
(gCO2eq/kWh)
Low-carbon
19%
Renewable
19%
Electricity production | Carbon emissions
by source
0GW
1GW
2GW
wind
solar
hydro
hydro storage
geothermal
biomass
nuclear
gas
coal
oil
unknown
AUS-VIC
Carbon intensity in the last 24 hours
Get historical data and forecast API
400
300
200
100
0
12:00 AM
6:00 AM
12:00 PM
6:00 PM
Origin of electricity in the last 24 hours
Show ranking
Carbon intensity:
Australia (South Australia): 406 gCO2eq/kWh
Low-carbon: 19 %
Renewable: 19 %
Carbon intensity (gCO2eq/kWh)
0
400
800
8:41 PM
21/11/2017


What is ITER?
Home - ANSTO
ANSTO - Home
Electricity Map | Live CO
Secure
https://www.electricitymap.org/?wind=false&solar=false&page=country&countryCode=AUS-QLD
Apps
Citrix Receiver - PPAC
TripIt | Online travel
Todoist
Google Calendar
IEA Stats
Electricity data brows
Electricity Map | Live
G. B. National Grid st
Other book
Electricity Map | Live CO2 emissions of electricity consumption
Australia (Queensland)
November 21, 2017 8:29 PM
Carbon Intensity
Low-carbon
Renewable
770g
1%
1%
(gCO2eq/kWh)
Electricity production | Carbon emissions
by source
0GW
2GW
4GW
6GW
8GW
wind
solar
hydro
hydro storage
geothermal
biomass
nuclear
gas
coal
oil
unknown
AUS-NSW
Carbon intensity in the last 24 hours
Get historical data and forecast API
pro
800
600
400
200
0
12:00 AM
6:00 AM
12:00 PM
6:00 PM
Origin of electricity in the last 24 hours
Show ranking
Carbon intensity:
Australia (Queensland): 770 gCO2eq/kWh
Low-carbon: 1 %
Renewable: 1 %
Carbon intensity (gCO2eq/kWh)
0
400
800
Like
8:43 PM
21/11/2017