BENEFITS OF NUCLEAR ENERGY FOR REMOTE INDUSTRIAL APPLICATIONS

PETER ZAJAC
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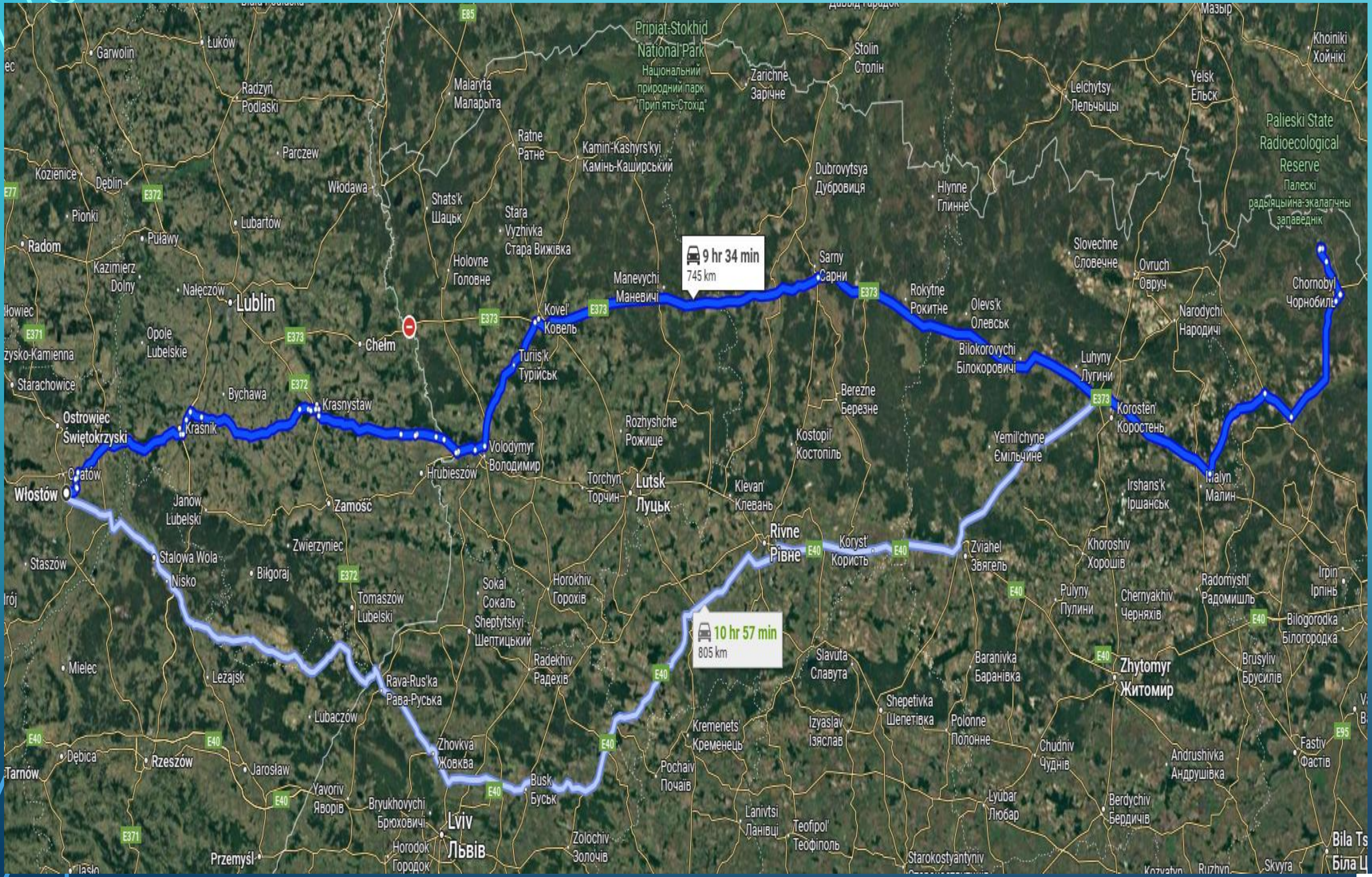
INTRODUCTION

I was born and raised 745km from Chernobyl Nuclear Power Plant (Google Maps)- under 700km in straight line



I remember the 26th of April 1986

I still haven't grown any additional limbs, third eye on my forehead. I HAVE LOST SOME HAIR SINCE- DUE TO PEOPLE ST*TY.**

I want my tax money back from Australian Conservation Foundation

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WHAT DIFFERENTIATES OFF-GRID, ISLANDED, INDUSTRIAL INSTALLATIONS FROM LARGE INTERCONNECTED GRIDS

- Size- remote industrial operations vary from small <10MW to large >500MW (still much smaller than multi-GW grids)
- Less prone to diurnal and seasonal load fluctuations. Load size is typically constant in steady state
- Ratio of size a single largest load to a single generator (and total generation) is smaller, meaning that trip of a single large load has greater impact on frequency and voltage, and may have larger implication on system stability
- Islanded industrial systems are typically supplied by reciprocating engine generators (gas, diesel, HFO- heavy fuel oil- marine fuel) and gas turbines, or combination. Those are low inertia devices (constant of inertia between 0.5s (small engine generators) - 1.5s (aeroderivative gas turbine), compared to 6-10s for large steam turbines

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EXAMPLE OF FLOATING POWER STATION-PNG

CHALLENGERS FACED BY INDUSTRIAL SYSTEMS

- Trip of one large load can cause instability
- Mining operation are typically operating mills, that are largest single loads. Trip of a mill (SAG mill being a large load) may affect system frequency and may cause cascading trips
- Starting of the mill typically requires more spinning reserve than normal operation, therefore more generation is required online during large motor start-up. Additional generators need to be started, and then may be stopped when the mill is running
- Large motors like mills can trip based on processing issues, up to multiple times per week, affecting system total load in a steady state
- Compressors are another group of large loads
- Underground mines use large chiller systems for mining shafts, and winders. Winders are typically fast fluctuating loads, with short repetitive cycles (power fluctuations up to 10MW with cycles lasting tens to hundreds of seconds). Thia may mean that the site load varies by 10% every 2 minutes (10MW winder in 100MW system)

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CHALLENGERS AND MYTHS OF USING RENEWABLES IN REMOTE OFF-GRID SYSTEMS

- High Renewable Penetration (Microgrid)- Success Story, Myth, or indication of hard limits ????- Jabiru https://edlenergy.com/project/jabiru/

At a glance

Project name:
Jabiru Hybrid Renewable Power Station

Owner, operator:
EDL

Start of operation:
February 2022

Location:
Jabiru, Northern Territory, Australia

Generating capacity:
8.4 MW

Primary fuel:
Hybrid

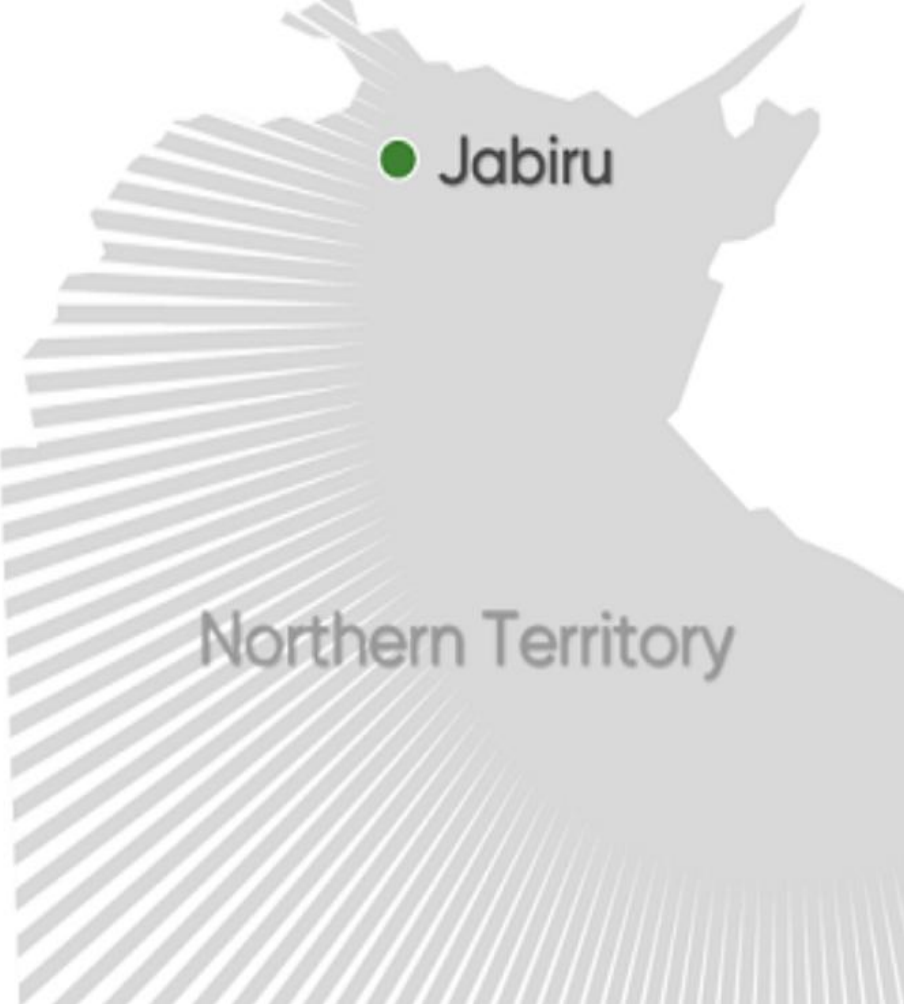
Generating capacity (solar):
3.9 MW

Generating capacity (diesel) :
4.5 MW

Electricity generated:
~13.4 GWh p.a.

Equivalent homes powered:
~2,400 p.a.

***Data sourced from:**
CY23



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CHALLENGERS AND MYTHS OF USING RENEWABLES IN REMOTE OFF-GRID SYSTEMS

- Jabiru Power Station

CHALLENGERS AND MYTHS OF USING RENEWABLES IN REMOTE OFF-GRID SYSTEMS

- Electricity generated annually- 13,400 MWh
- Electricity generated daily (average)- 36.7MWh
- Electricity generated per hr (average)- 1.53MWh (max demand during daily peak hours ~2.1MW), meaning variation between day and night load
- Generating and storage sources:
  - ✓ 4.5MW diesel generation- <u>5 Engine Generators</u>
  - ✓ 3.9MWdc solar- 1 Inverter (No Redundancy)
  - ✓ 3MW / 5MWh battery- 2 inverters + 2 Battery Enclosures
- Number of blackouts and or load shed operations per year- not listed / not known

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CHALLENGERS AND MYTHS OF USING RENEWABLES IN REMOTE OFF-GRID SYSTEMS

- Listed average annual renewable penetration- 50%
- Autonomy time on renewables ONLY in bad weather during the day when BESS fully charged <2hr (before diesel generation is dispatched)
- Typical CAPEX required for supply and installation (based on economy of scale, prices would vary depending on installation size, location, etc.):
  - ✓ Solar- $1.3M-$1.5M / MWdc- total ~$5.5M
  - ✓ Diesel- $1.3M -$1.5M / MW- total ~ $5.5M
  - ✓ BESS- $1M - $1.2M / MWh @ given MW- total ~ $6M
- Switchgear cost is excluded, as it is required irrespectively of the type of generation used
- For an average load of 1.5MW, this means CAPEX of ~$11M per MW (for 2hr Autonomy)

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CHALLENGERS AND MYTHS OF USING RENEWABLES IN REMOTE OFF-GRID SYSTEMS- THEORETICAL CASE

- Let's have a look at a theoretical 1MW system, operating 24/7, with 100% renewables for 5 days (very coarse calculation). 5 days of bad weather in a row are not unusual
  - ✓ 1MW- 24MWh per day, 120MWh for 5 days
  - ✓ Let's assume solar produces energy in MWh of 600% its DC MW rating on a good day and 100% on a bad day (energy production is scattered unevenly over a period of 8-10hours, with 3hr peak). Load is steady, 1MW every hour
  - ✓ Approximately 100MWh of BESS would be required
  - ✓ Now, the calculation becomes statistical, how many good weather days precede 5 days of bad weather. Which is a problem on its own. Let's assume 10 days of good weather and 5 days of bad weather
  - ✓ 10 good days to feed load and charge battery (with BESS charging and discharging energy in a meantime, with AC RTE of 85%, but let's disregard loses for now)

CHALLENGERS AND MYTHS OF USING RENEWABLES IN REMOTE OFF-GRID SYSTEMS- THEORETICAL CASE

- Let's have a look at the theoretical 1MW mining system, operating 24/7, with 100% renewables for autonomy of 5 days (very coarse calculation). 5 days of bad weather in a row can be easily expected (ASSUMPTION: STARTING 10 DAYS WITH BESS DISCHARGED)
  - ✓ Theoretical solar needs to, in 10 days, produce 100MWh to charge the BESS, plus needs, DIRECTLY AND INDIRECTLY, to feed 240MWh to the load, either directly or via BESS
  - ✓ This means 340MWh over 10 days, 34MWh per day
  - ✓ Loses excluded, this would require 6MWdc solar farm
- So, for 100% renewable penetration for 5 days, cost of generation and storage would be:
  - ✓ Solar ~$8.4M
  - ✓ BESS likely **>$50M**
- Statistically, achieving 100% renewable penetration is not economically viable, and there is still a question **"Fully renewable- For how long ?????"**

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CHALLENGERS AND MYTHS OF USING RENEWABLES IN REMOTE OFF-GRID SYSTEMS- THEORETICAL CASE

- At the same time, diesel (no the cheapest fuel) generator of small size, needs about 250l per MWh (when running 3 generators at 66% rating, for redundancy and spinning reserve)
- In 20 years, that diesel generators will use ~44M litres of diesel
- When buying in bulk, cost of diesel would be ~$1/l, say $1.2/l
- Total cost of diesel for 20 years would be ~$52.5M
- So, statistically, excluding all stability issues (mentioned on next slide), weather events past 5 days, space requirements, decommissioning costs, etc. BESS/solar system capable of holding 1MW system for 5 days of bad weather, would ALMOST repay itself in approximately 20 years

The conclusion is:

POWER GENERATION SYSTEMS RUN ON FUEL, NOT ON STATISTICS

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CHALLENGERS AND MYTHS OF USING RENEWABLES IN REMOTE OFF-GRID SYSTEMS- THEORETICAL CASE

- Additionally, using 100% IBR would result in technical issues with:
  - ✓ System strength (fault power), which would further increase the cost (likely addition of synchronous condensers to allow solar to export energy)
  - ✓ Synchronous condensers would be also required for operating variable speed drives, correct protective equipment operation, supply of reactive power to the distribution system where OH lines are used
  - ✓ Harmonics and power quality

The reality is that small to medium penetration of renewables and storage may be beneficial for fuel savings, for peaking operation, for potential long-term operation cost reduction (CAPEX vs OPEX studies are crucial, comparison of $/MW and $/MWh costs).

Fully "renewable" systems are not technically or economically viable

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FUEL SUPPLY CHAIN IN REMOTE OFF-GRID SYSTEMS

- In remote systems engine generators and gas turbines are the cheapest generating plant to install. Where local supply of fuel is available (gas fields, access to biogas), cost of installation and operation of engine generators and turbines is lower than any other source of energy
- Remote isolated areas face separate challenges. Let's look at the supply chain of LNG for an example of remote location with no pipeline or limited roads:
  - ✓ Likely construction of the port / modification of the port is needed, or optionally, floating storage vessel would be required. This will depend on the size of LNG tanker available
  - ✓ If there is no supply contract, or the location is not in the established supply route, new ship may be required, suitable for the local ports, etc.
  - ✓ Where road supply is required, there may be a requirement for new roads, trucks, storage facilities
  - ✓ Those can add to the cost significantly

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FUEL SUPPLY CHAIN IN REMOTE OFF-GRID SYSTEMS

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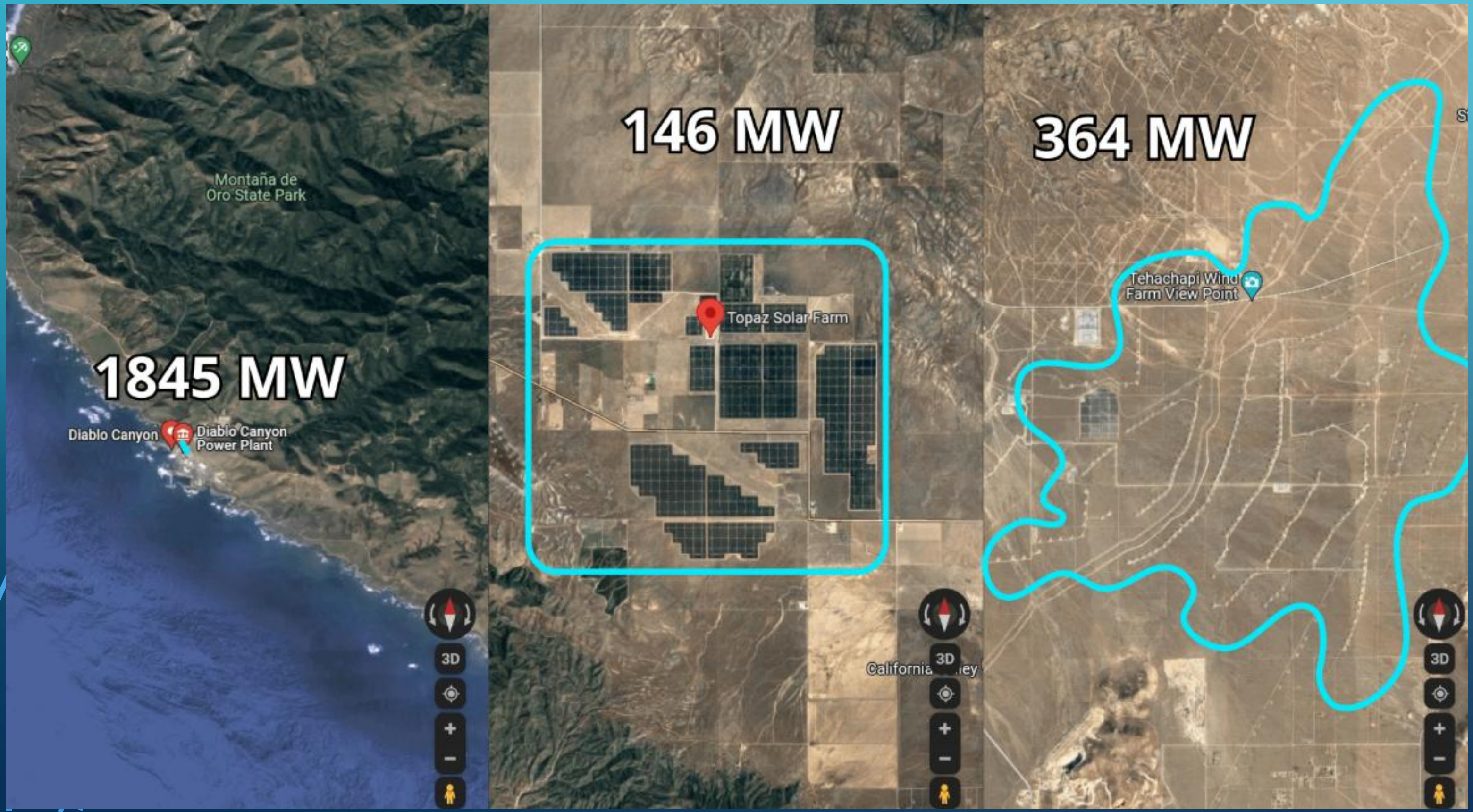
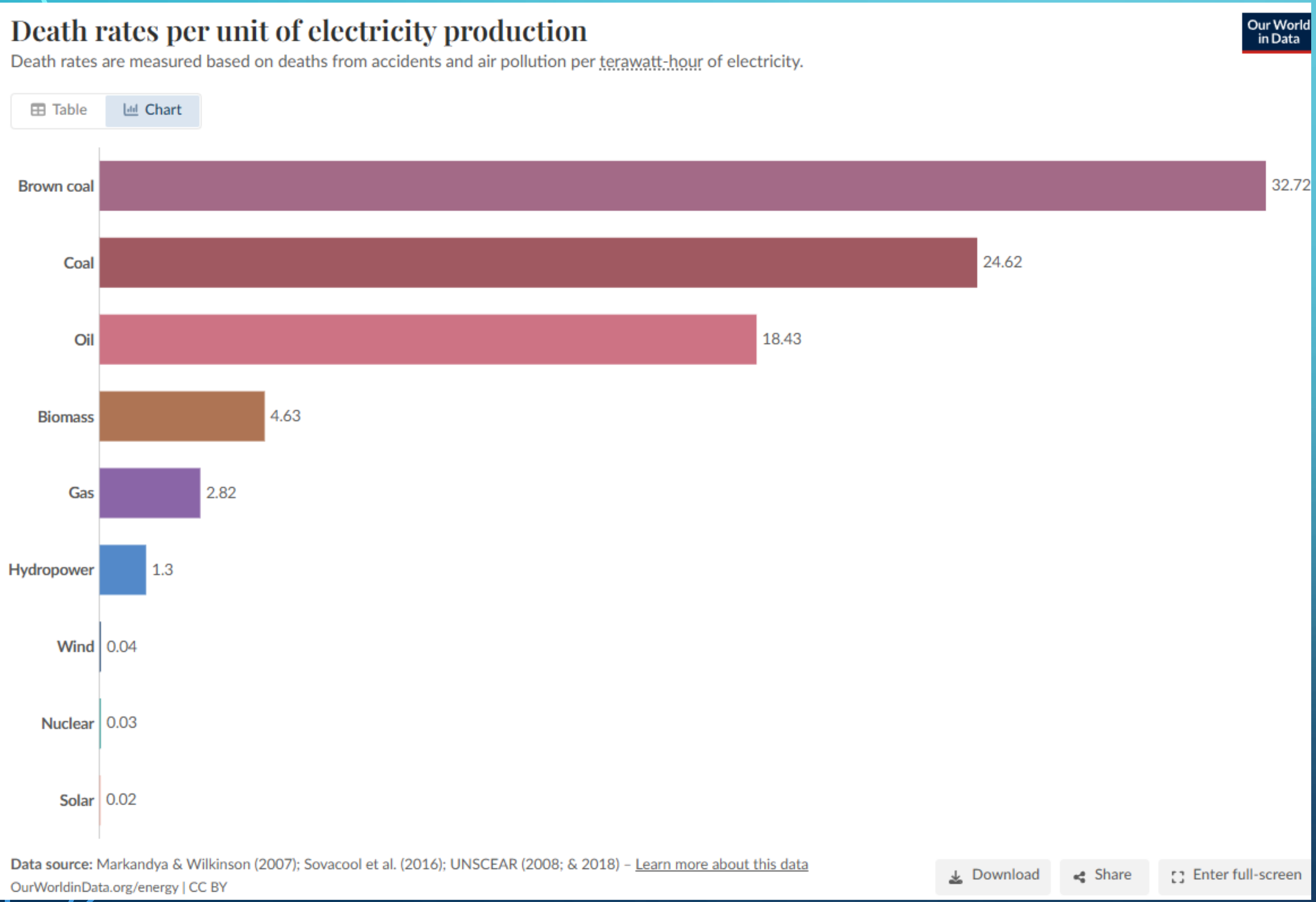
WHY NUCLEAR

- Weather independent, fully dispatchable
- High availability factor (over 90%)
- Highest energy density (lowest area required per MWh), which is extremely important in areas that have ore pockets that may / will be mined in the future, due to material cost uncertainty, or due to increase in demand



WHY NUCLEAR

- Lowest number of deaths per TWh per source of supply (2007 Markandya & Wilkinson, 2016 Sovacool et al. shown below do not include Texas and Iberia blackouts), yet still show nuclear in top three



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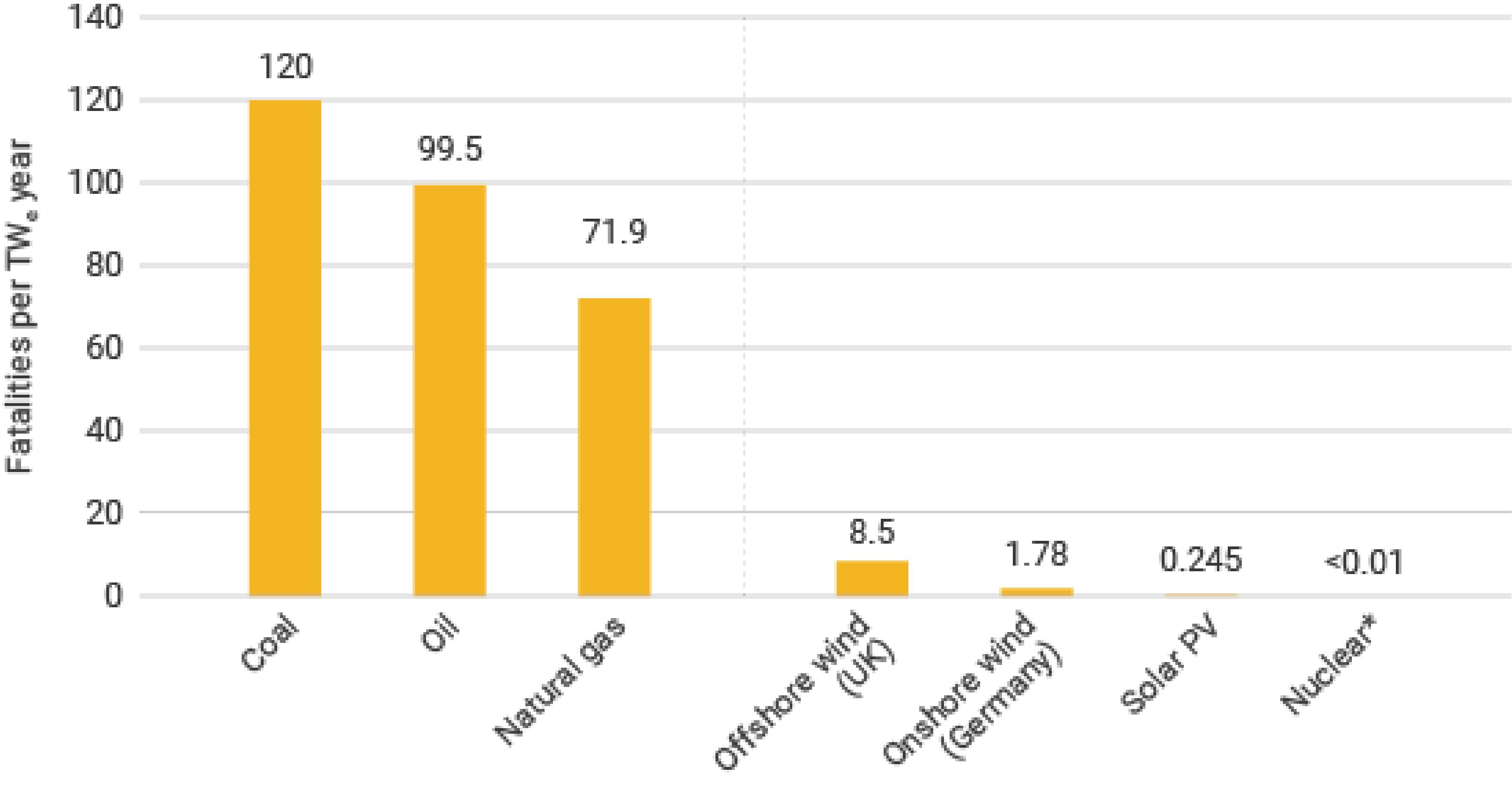
WHY NUCLEAR

- Lowest number of deaths per TWh per source of supply (source- https://world-nuclear.org/information-library/safety-and-security/safety-of-plants/safety-of-nuclear-power-reactors)



*Gen II PWR, Swiss.
Source: Paul Scherrer Institut. Data for nuclear accidents modified to reflect UNSCEAR findings/recommendations 2012 and NRC SOARCA study 2015

WHY NUCLEAR

- Long life- 40-60years for small reactors, compared to ~circa 20-25 years for renewables (less for batteries)
- Immune to weather events like hailstorms, high gust winds, cyclones, lightning storms, etc.
- Immune to man / mining made events
  - ✓ Tremors caused by blasting in mining
  - ✓ high dust from crushing / milling / processing / ore storage
- Can co-generate steam if/where required for processing (for example gold extraction in autoclaves), etc.

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Oh, but 30-50MWe reactor don’t exist ☺, there are none in operation,

only 300-2000MWe reactors are there

MEET AKADEMIK LOMONOSOV (PROFESSOR LOMONOSOV)

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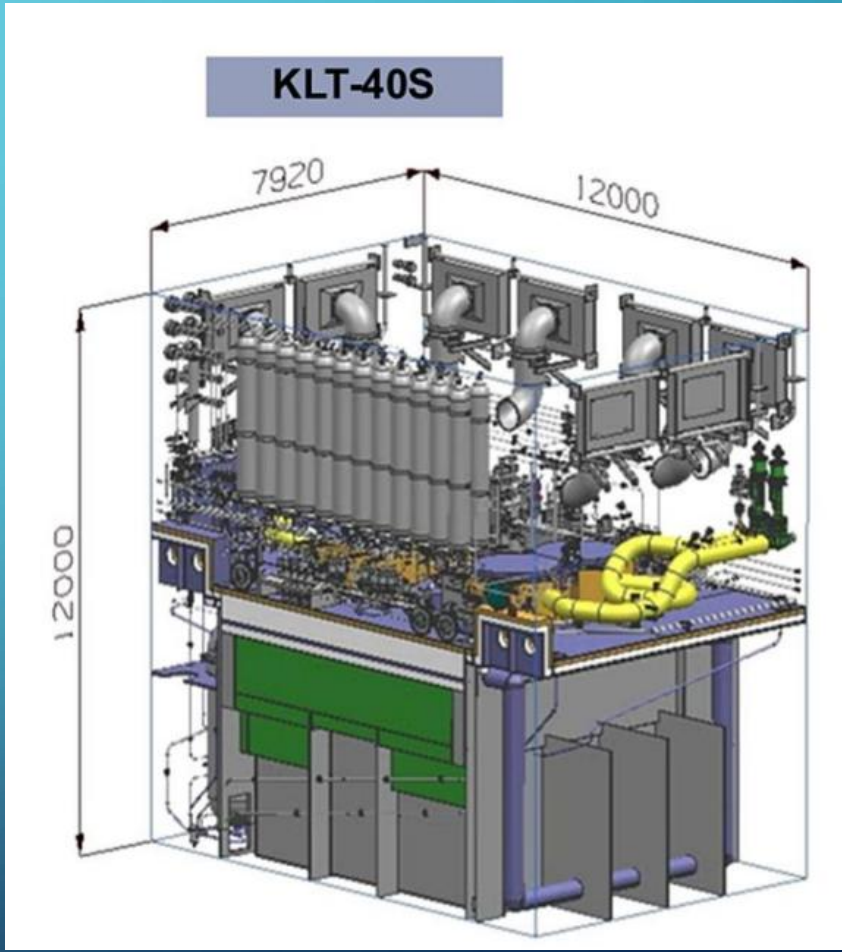
https://lynceans.org/wp-content/uploads/2021/05/Russia-Akademik-Lomonosov-FNPP-converted.pdf

- Two PWR reactors KLT-40S (35MWe Each)

Reactor facility	KLT-40S	RITM-200
Maximum power, MW:		
thermal	150	175
electric	35	55
Maximum electric power at maximum thermal power, MW	19.4	30.4
Thermal power at maximum electric power, MW	29	34
Mass within the containment shell, tons	1874	1100
Nominal service life of equipment, yr:		
not interchangeable	40	40
interchangeable	20	20

Parameter	Value
Reactor thermal power, MW	150
Fuel type	Cermet
Refuelling mode	Single loading with replacement of all FAs
Uranium inventory, kg	1273
Uranium-235 inventory, kg	179
Average uranium enrichment in the core, %	14.1
Fuel life at N_{rated}, eff.days	14 000
Operation period without refuelling, yr.	~ 2.3
Specific consumption of uranium-235, g ^{235}U/(MW·day)	2.05
Average fuel burnup fraction on oxide fuel basis, MW·day/kg U	45.4



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- Two PWR reactors KLT-40S (35MWe Each)
- 70MWe total output
- Total project cost, excl new infrastructure in town, was approximately USD460M (circa AUD9M / MW) according to available sources. Cost included quarters for 70 crew members onboard, which has increased the total price. This gives steady and predictable cost per kWh up to 2060
- Construction has started in 2007, and commercial operation began in 2020. Construction time was extended as the unit was repurposed, deployment location was changed
- It supplies a township of Pevek (approximate population of 4,162 people as per 2010 census). It will play a key role for gold mining project in the area, it provides supply to the Pevek port
- Fuel Requirements- <20% Enrichment, still considered LEU (Low Enriched Uranium) by IAEA

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- https://pris.iaea.org/PRIS/CountryStatistics/ReactorDetails.aspx?current=895

OPERATING HISTORY

Year	Electricity Supplied [GW.h]	Reference Unit Power [MW]	Annual Time On Line [h]	Operation Factor [%]	Energy Availability Factor [%]		Load Factor [%]	
					Annual	Cumulative	Annual	Cumulative
2019	0.680	32	312					
2020	64.930	32	5138	71.6	90.4	90.4	28.8	28.8
2021	125.260	32	7104	81.1	85.1	87.0	44.7	38.8
2022	74.130	32	6367	72.7	50.0	72.7	26.4	34.0
2023	74.630	32	5143	58.7	33.0	61.7	26.6	32.0
2024	144.910	32	8339	94.9	77.9	65.2	51.6	36.2

Performance indicators are calculated from the Commercial Operation Date.

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OTHER REACTORS OF SIMILAR SIZE

RITM-200 Series- Successor of KLT-40S

RITM-200

Reactor type	Integral
Installed capacity (t)	~ 175 MW
Installed capacity (e)	~ 50 MW
Evaporation capacity	248 t/h
Steam temperature	295 °C
Steam pressure	3.82 MPa
Lifecycle	60 years
Fuel campaign	4 - 6 years
Capacity factor	90%
Fuel enrichment	< 20%
Size, L x W x H	6.0 x 6.0 x 15.5 m
Fuel Assemblies	199

10 Reactors Constructed, 8 in operation, 2 being commissioned
8 Additional reactors in production as of March 2025

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CHALLENGES AND SOLUTIONS FOR NUCLEAR GENERATION

- Nuclear reactors- big or small, are designated mainly for baseload supply, similarly to all steam turbines
  - ✓ Nuclear can be mixed with various types of energy storage, depending on the operation
  - ✓ In processing facilities using Oxygen for processing, Oxygen storage could be used to vary power supply requirements during peak periods
  - ✓ Where tailings dams are used by processing facilities, and water is reused for processing, tailings dams which are built for the facilities, could be used as pumped hydro stations
- Single reactor solution is not applicable as failure may result in prolonged outages:
  - ✓ As mentioned in previous slides, various sizes of reactors are available to provide redundancy, of multiple reactors can be installed to allow for refuelling. Additionally, refuelling can be lined up for mine major shutdowns, where load is significantly lower, and could be supplied by other sources
- Reaction to fluctuating loads and to frequent starts / stops of the equipment (slower response)
  - ✓ Nuclear is the cheapest form of energy to operate (similar cost to coal fired). Battery storage could be used to accommodate fast fluctuating loads. Due to low cost of energy, and small portion of load to be covered by BESS, combination of nuclear with BESS, and other sources of energy storage, creates a valid case for a mix
- Installation time
  - ✓ Mining construction takes between 7 (very optimistic, small mines mainly) and 15 years (sometimes more) between exploration and operation, so cost of nuclear power station construction (majority offsite) is not a limiting factor
- Safety and Security
  - ✓ Mining operations are often remote, in non accessible areas, plus, precious metal mines (gold / silver, etc.) are typically protected by armed guards

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MORE DATA RE NUCLEAR FLEET AND ICEBREAKERS

https://gnssn.iaea.org/NSNI/SMRP/Shared%20Documents/TM%202%20-%205%20October%202017/SMR%20Technology%20Development%20in%20Russia%20and%20Capacity%20Building%20Supports%20for%20Embarking%20Countries.pdf

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CONTACT DETAILS

Peter Zajac

ZW Solutions

Mobile: +61 405 903 007

Email: Peter.Zajac@ZWSolutions.com.au

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