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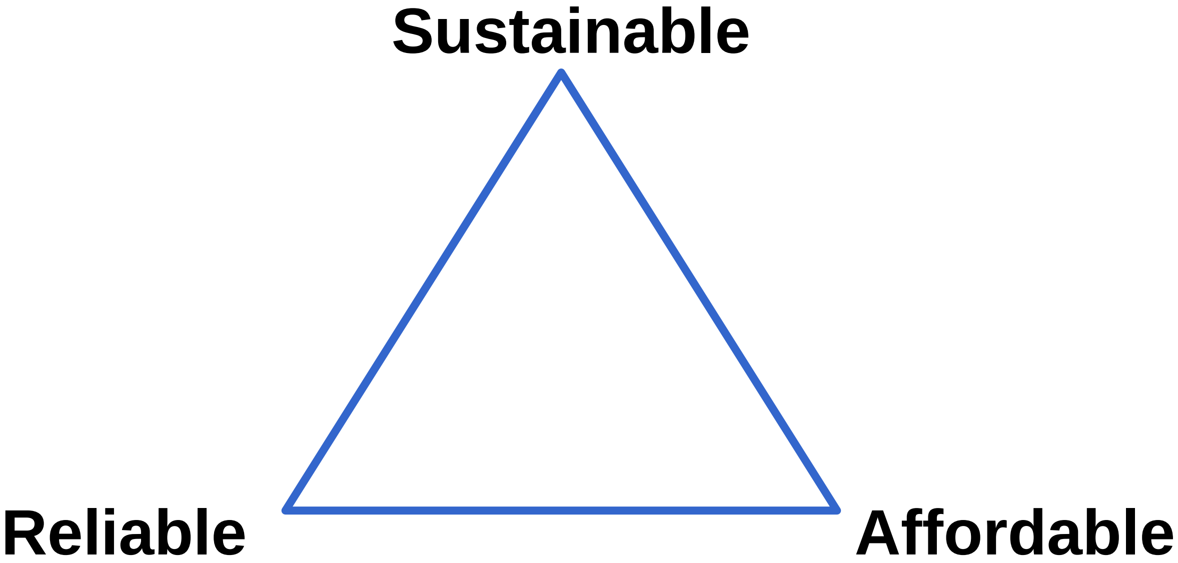
Nuclear Energy in Climate Resilient, Low Carbon Power Systems

14th International Conference of the Croatian Nuclear Society: Nuclear Option for Resilient Electricity Generation

Brianna Lazerwitz
Planning and Economic Studies Section, Department of Nuclear Energy
International Atomic Energy Agency

Optimal grid



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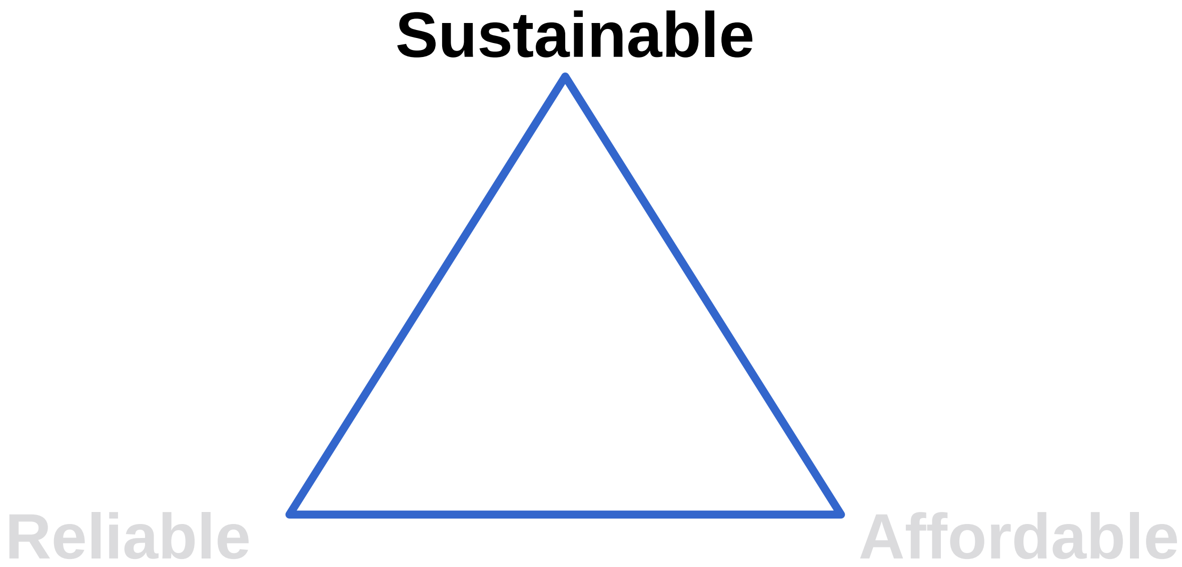
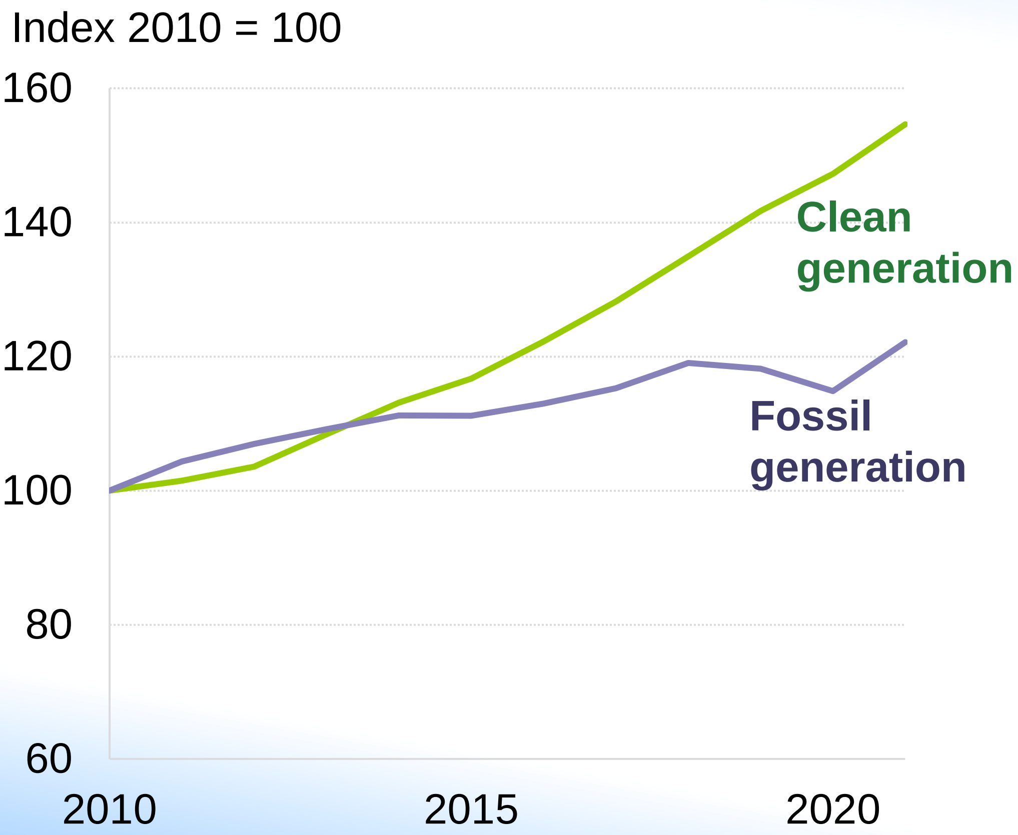
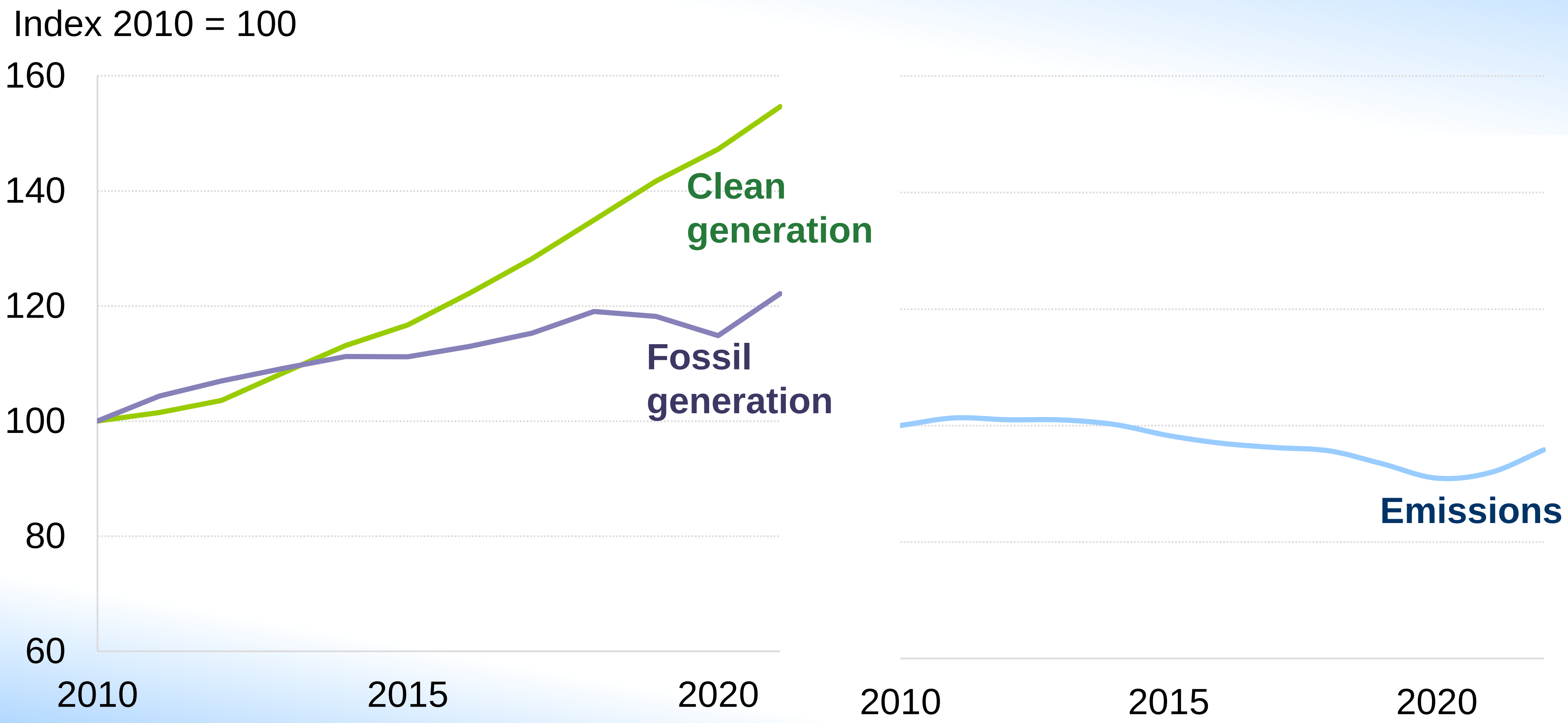


Increasing demand for clean energy



Source: Ember Yearly Electricity Data

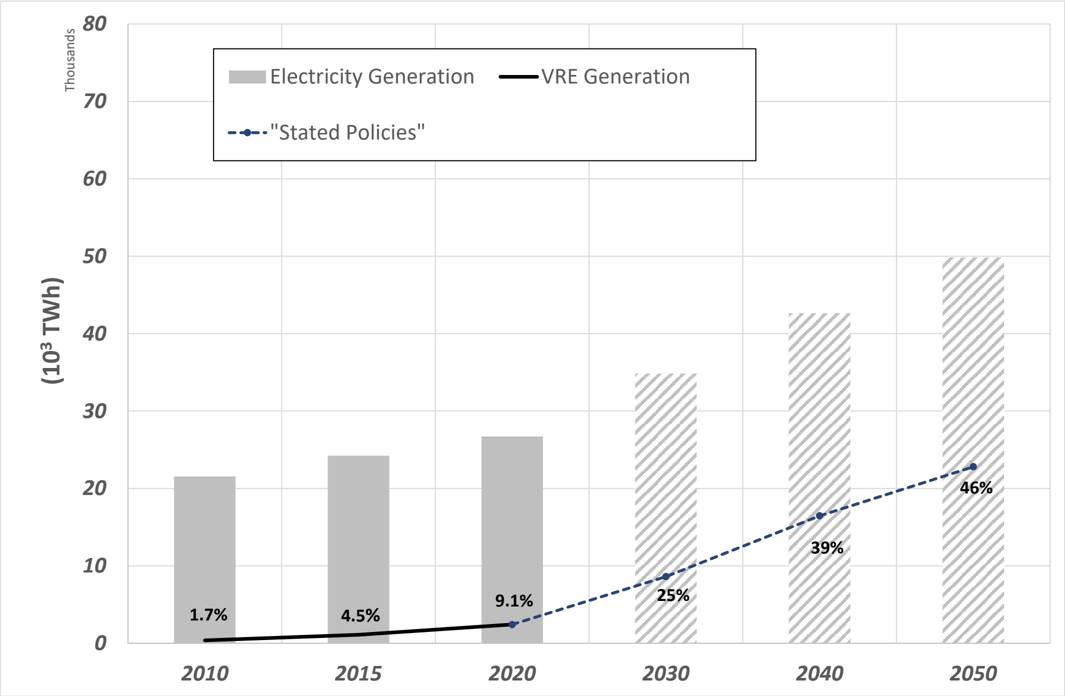
Limited impact on emissions (so far)



Source: Ember Yearly Electricity Data

Shift towards renewables

Global electricity generation – IEA World Energy Outlook



Source: IEA WEO 2023

Shift towards renewables

IAEA

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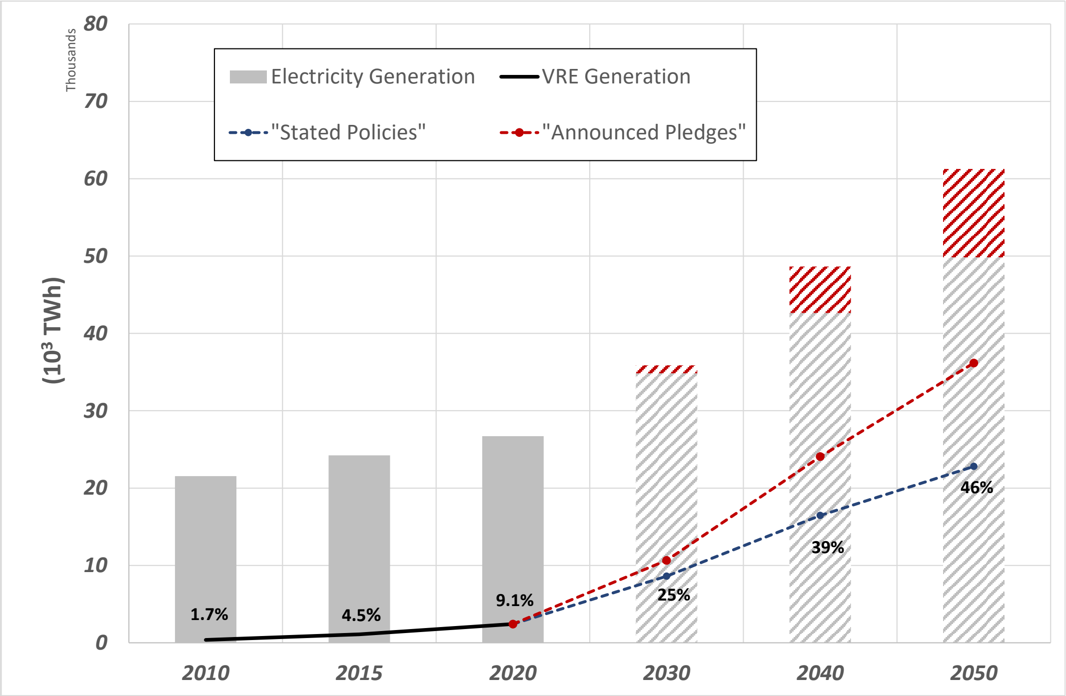

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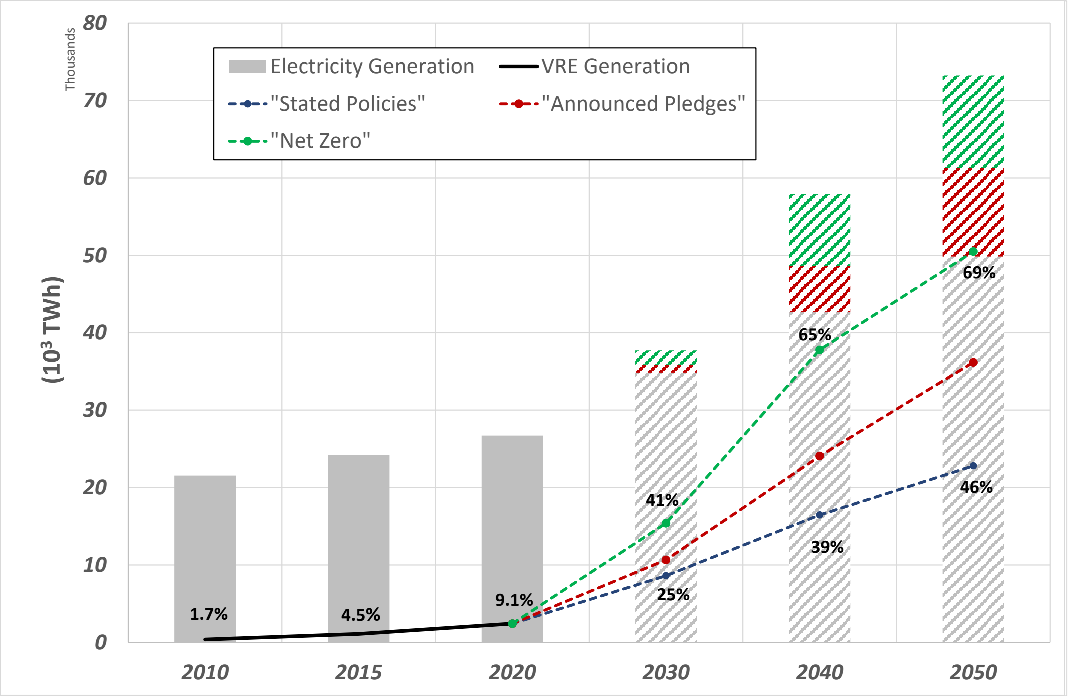

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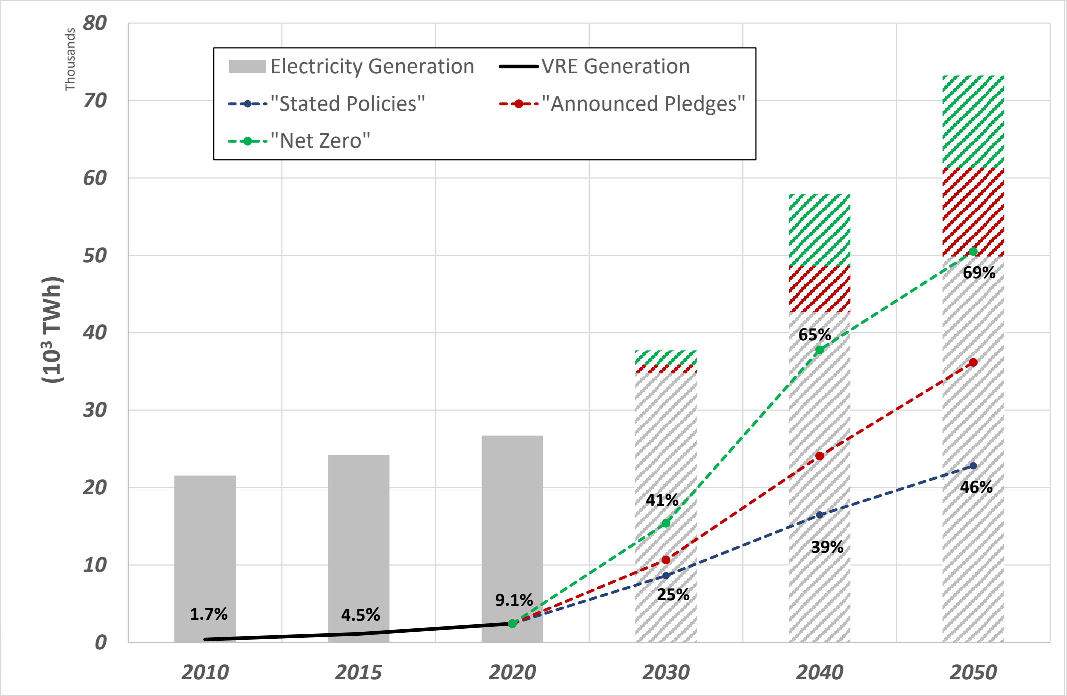
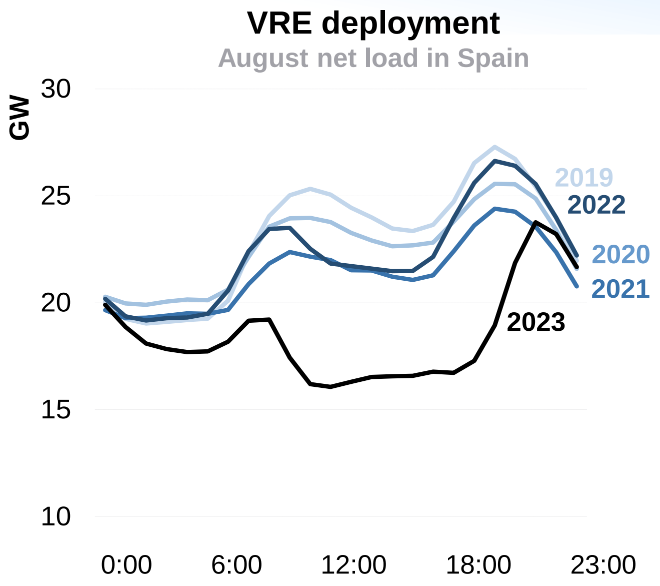
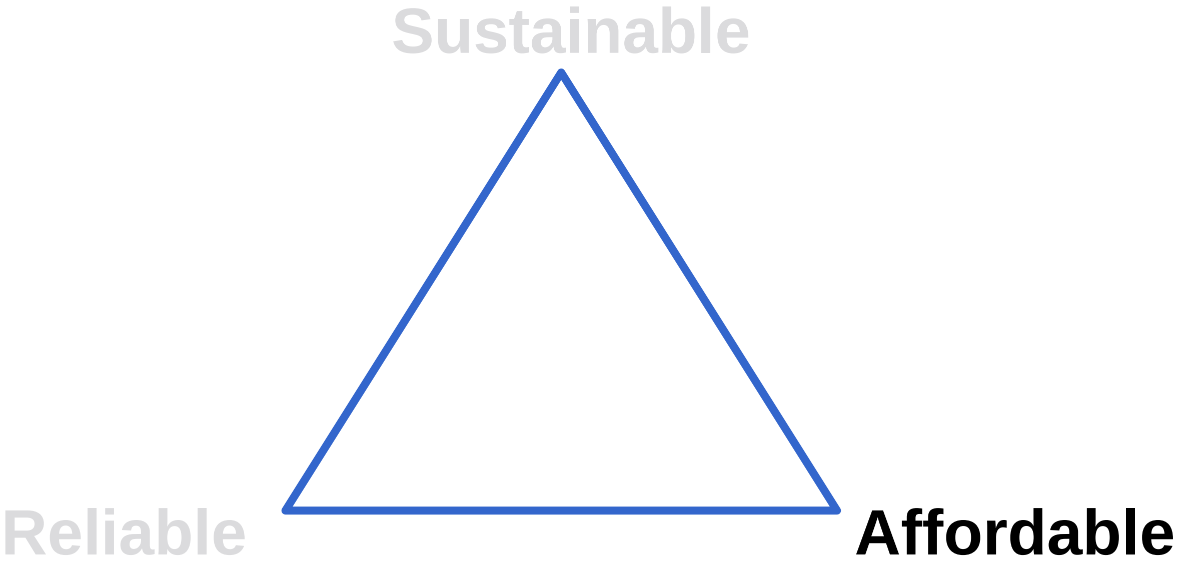




Source: IEA WEO 2023

Optimal grid



Using nuclear to meet demand and lower the overall cost of reaching NZ

- Meeting energy demand with **renewables alone** would require **enormous deployment rates** paired with **massive storage capabilities (very expensive)**, plus a much higher dependency on **critical minerals.**
    - This type of system is also likely to **extend reliance on fossil fuels**, since reaching 100% renewables is very costly due to a **small number of hours that require meeting high levels of energy demand** which often occur in extreme weather conditions.

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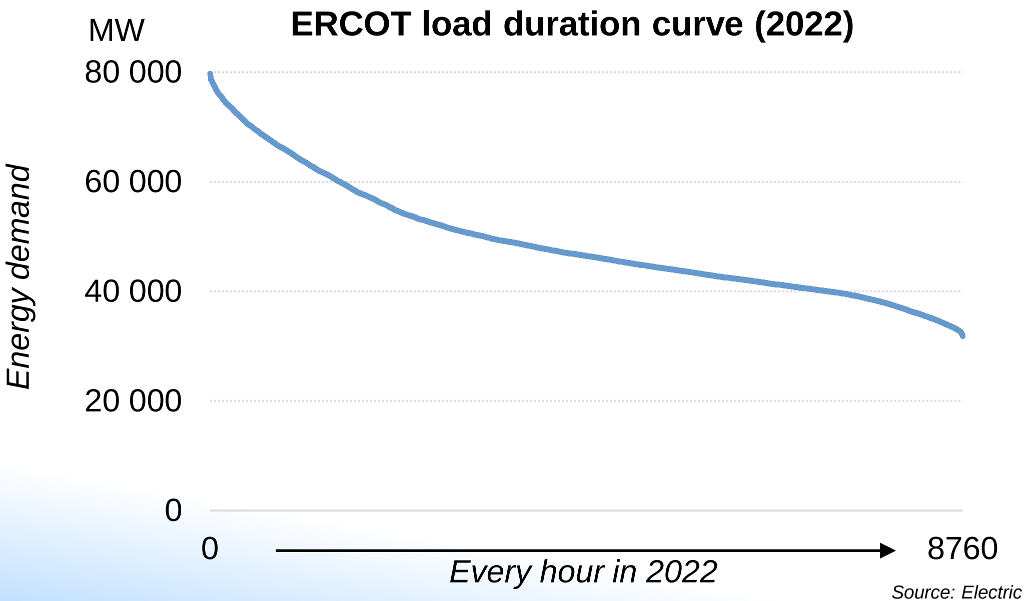
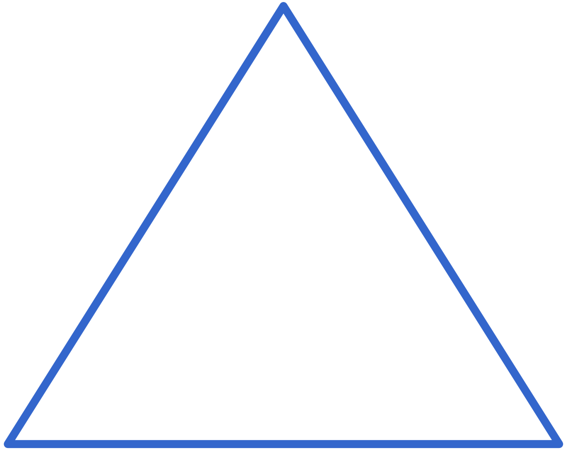
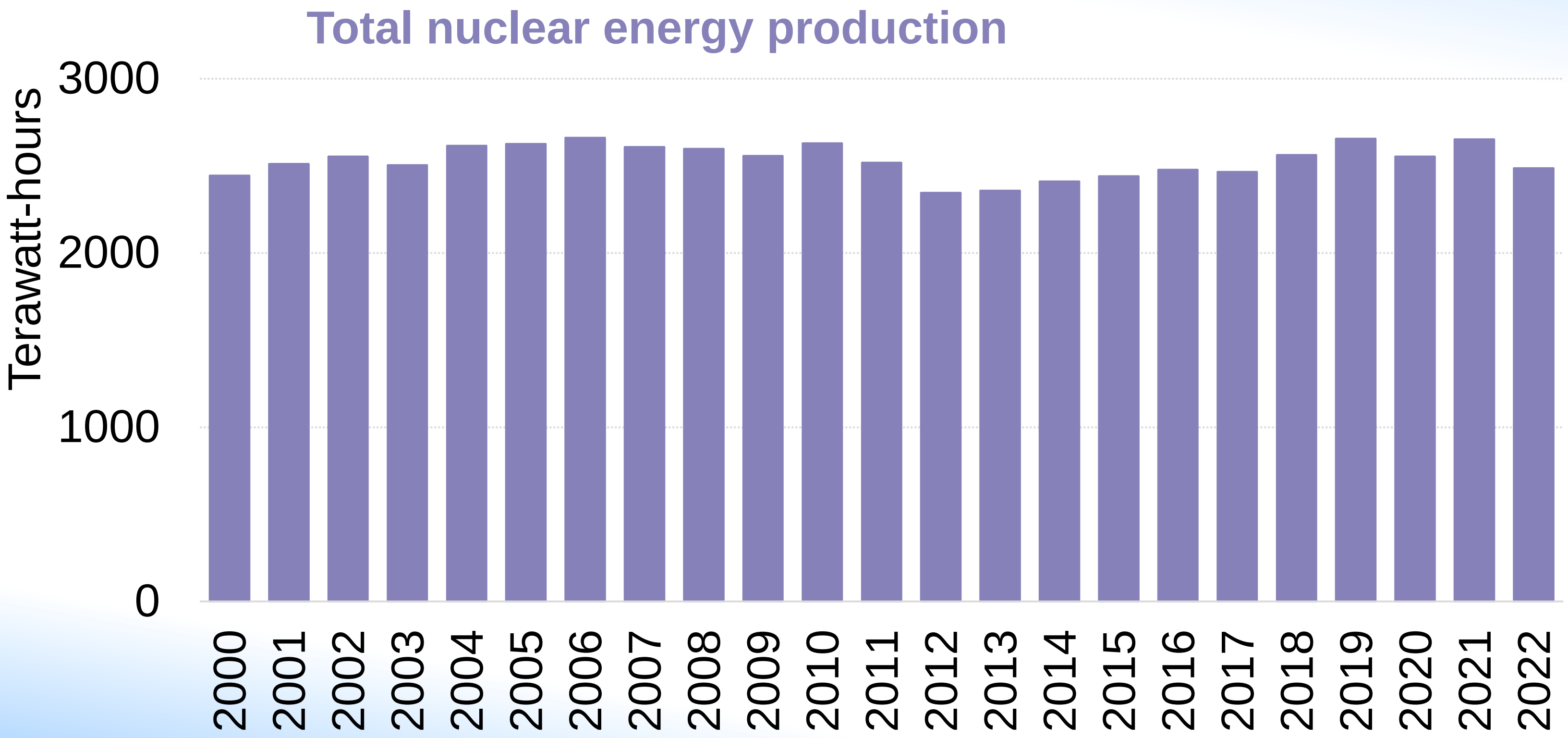


Source: *Electric Reliability Council of Texas native load data*

Optimal grid

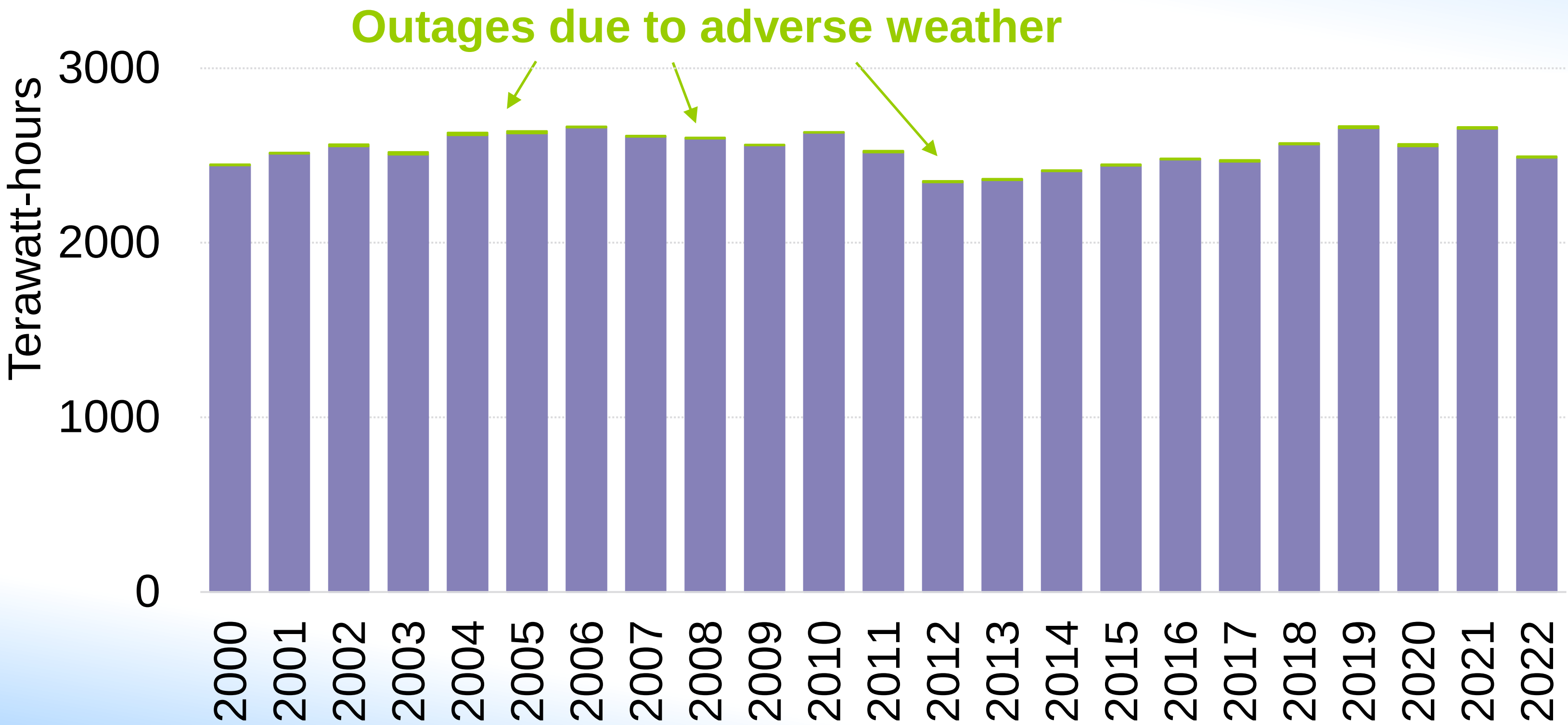


Nuclear performance during extreme weather conditions



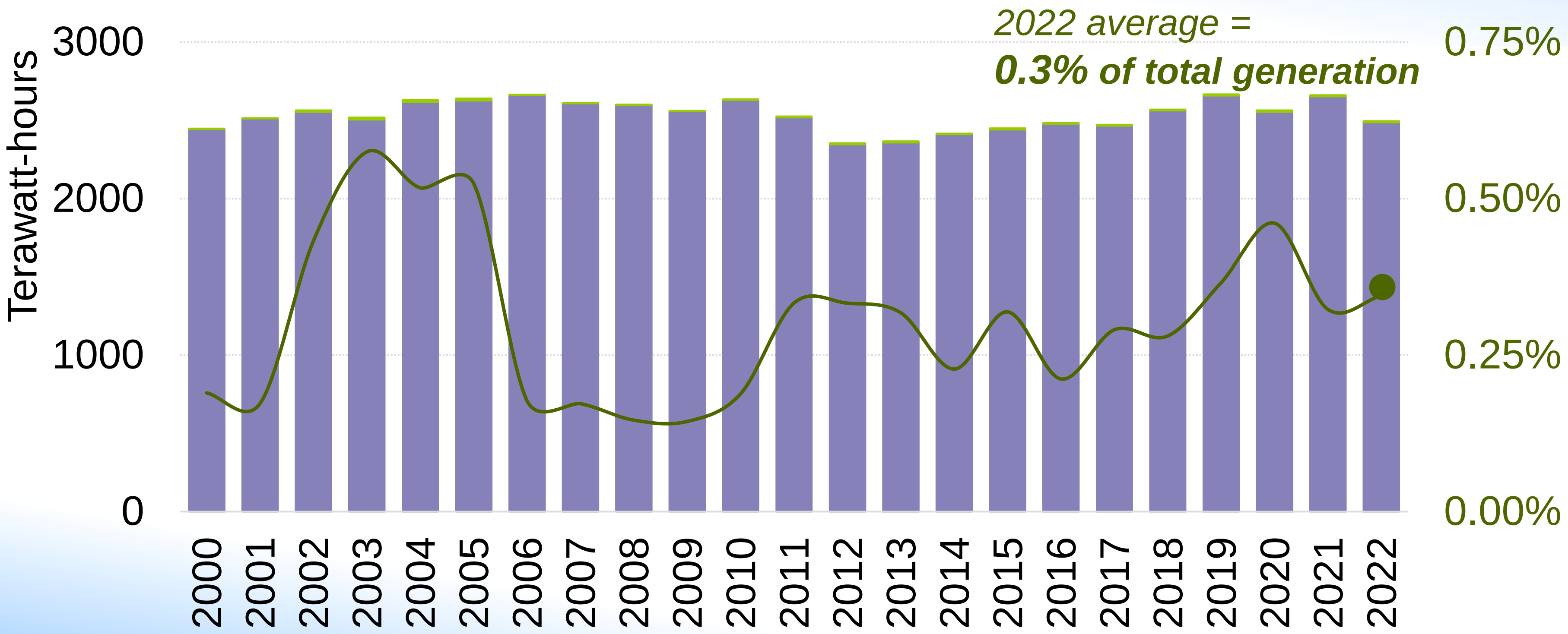
Source: IAEA Power Reactor Information System (PRIS)

Nuclear performance during extreme weather conditions



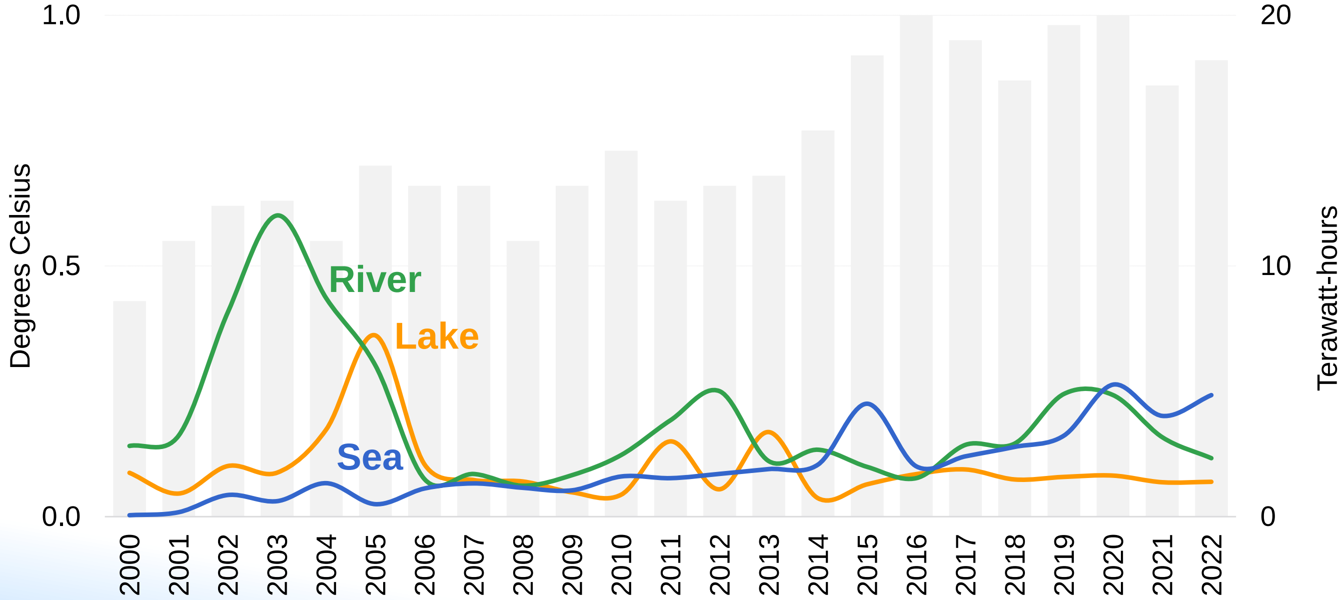
Source: IAEA Power Reactor Information System (PRIS)

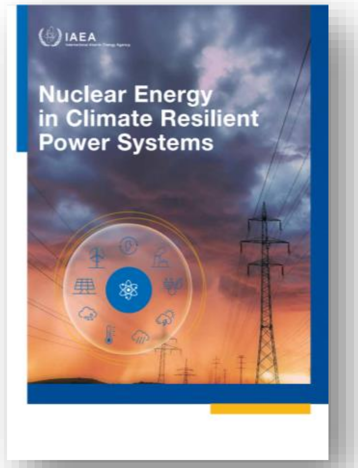
Nuclear's climate resilience track record



Source: IAEA Power Reactor Information System (PRIS)

Global temperature anomalies and weather-related nuclear energy losses





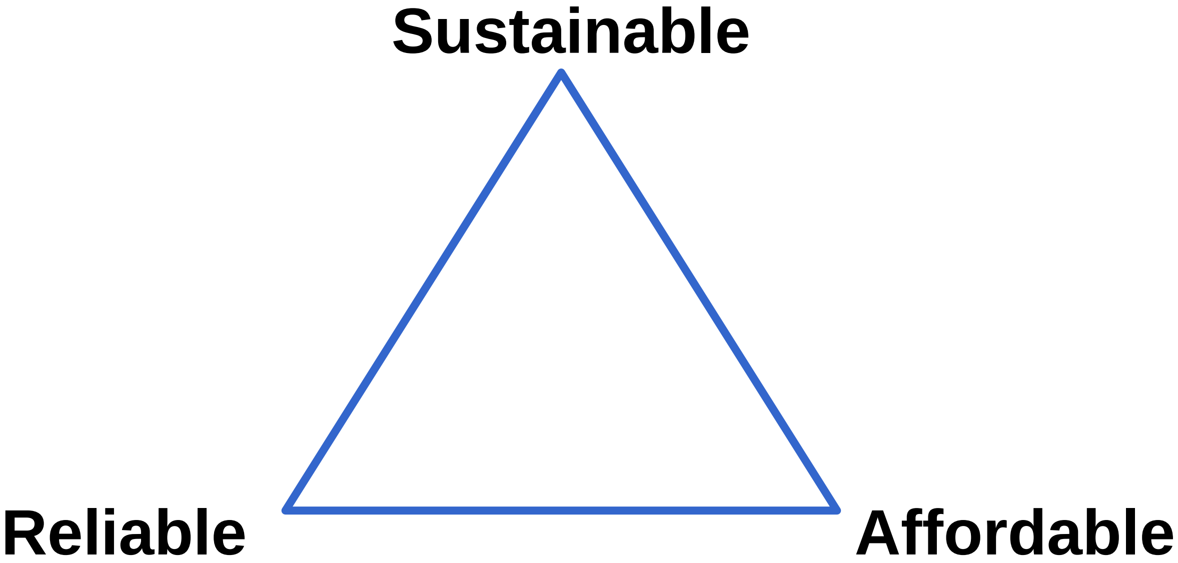
Released Sept. 2023

Source: IAEA Power Reactor Information System (PRIS); U.S. National Oceanic and Atmospheric Association (NOAA)

Synergistic attributes of nuclear energy

Implications for nuclear in global energy transitions

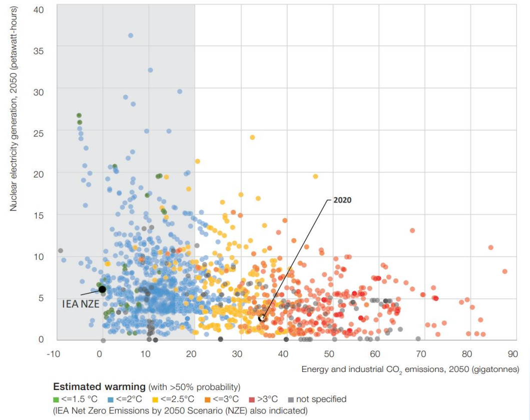
Optimal grid



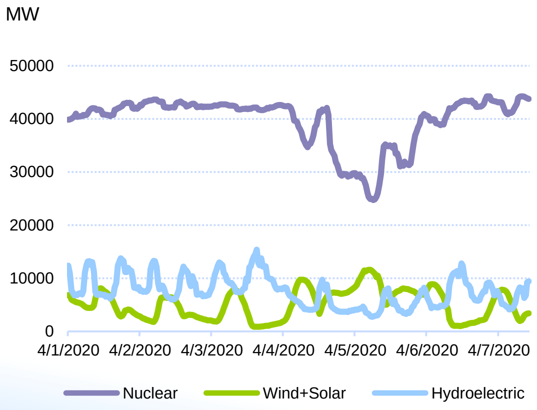
Achieving a sustainable future

Alongside other low-carbon energy sources, advanced nuclear technologies can help to

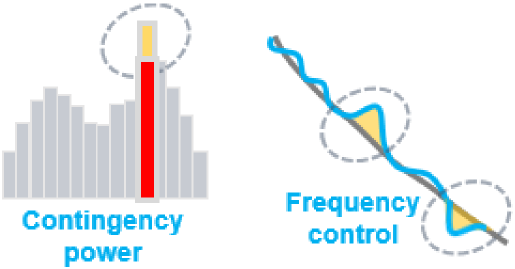
Drive climate and decarbonization goals



Ensure energy system diversity and security

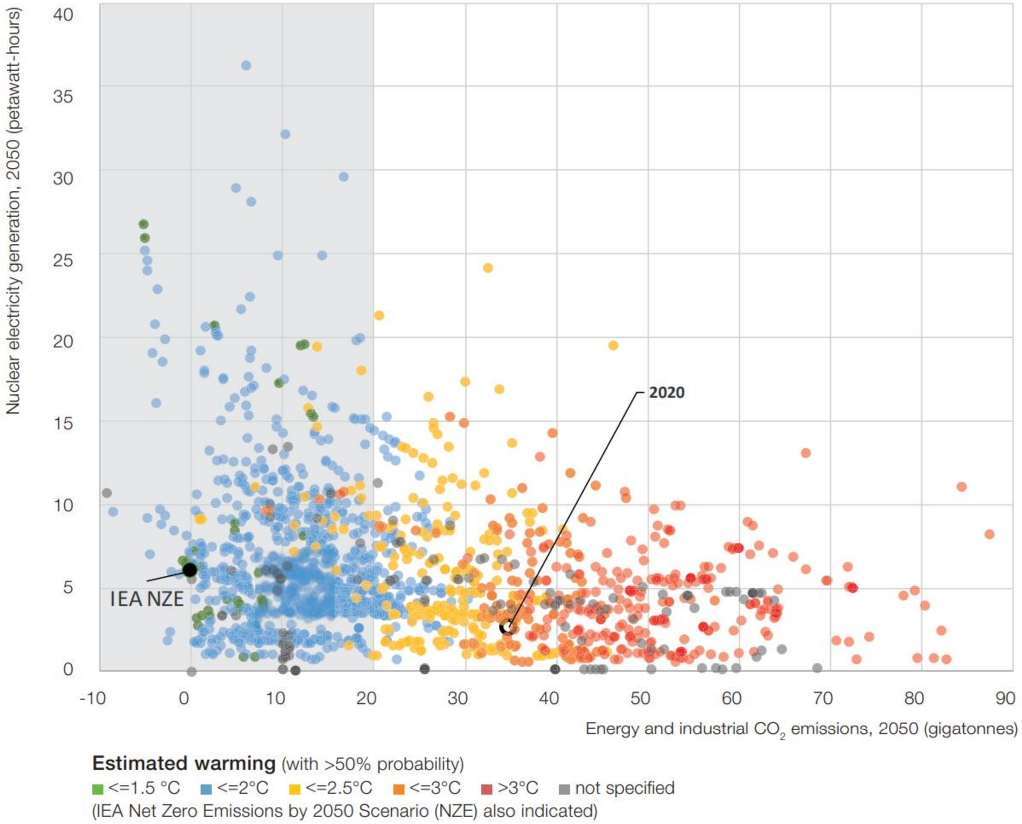


Enhance energy infrastructure resilience



Climate and decarbonization

Nuclear electricity generation and CO_2 emissions, 2050



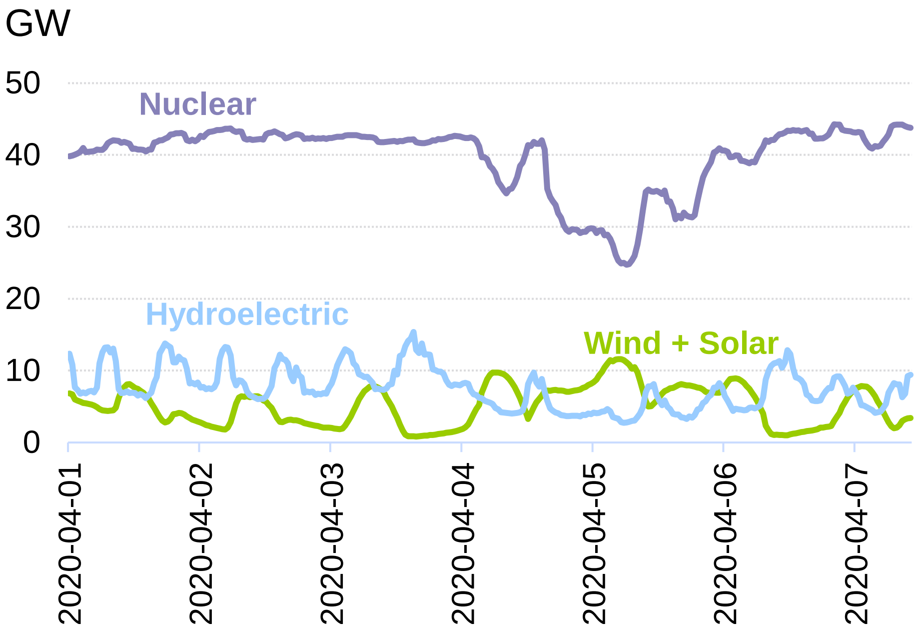
- Low emission energy source
- Enables greater integration of renewables and reduces the need for fossil fuel backup
- Lower investment ranges compared to traditional large reactors
- May be deployed as a replacement for fossil fuel-based power generation (coal-to-nuclear)

Source: IAEA

Energy diversity and security of supply

- Flexibility of nuclear (in general)
- SMRs offer modularity of deployment, helping to meet the challenges of meeting demand in an evolving energy landscape
- Distributed generation model reactors to be deployed near end-users / in isolated geographies
- Complementarity of dispatch with renewables – SMRs can enhance grid stability with location-specific deployment

France electricity generation, April 2020

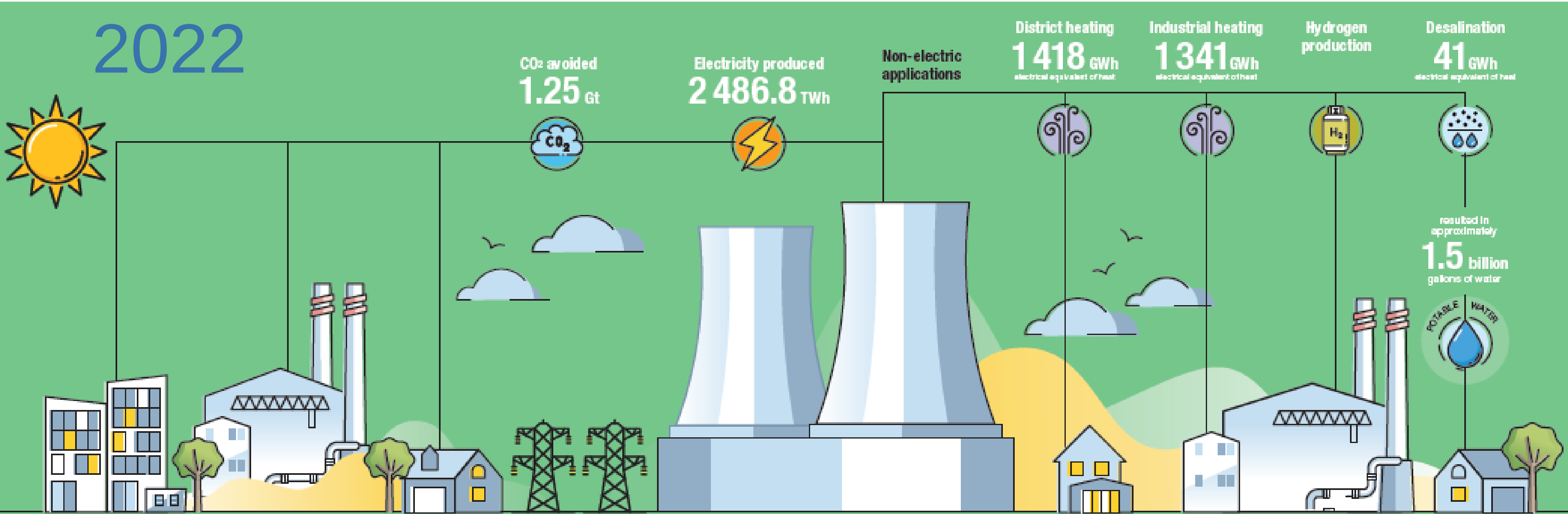


Source: RTE (France)

Decarbonization beyond power

Low carbon energy systems will be complex and highly integrated

SMRs can provide various scalable, low carbon products to sustainable energy systems, including electricity production only, cogeneration of electricity and industrial process heat, and various non-electric applications



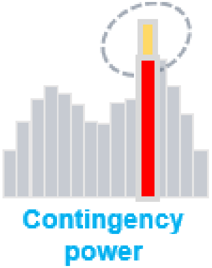
Source: IAEA PRIS

Resilience of energy infrastructure

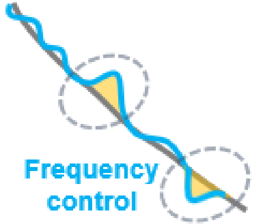
Seasons
Dispatchable power

Hours
Day-ahead markets

Minutes
Spinning reserves



Seconds
Balancing services



- Non-tangible energy infrastructure via grid support services: management of seasonal imbalances via the optimisation of planned outages, load modulation, balancing, inertia and voltage regulation
- Optimizing energy production and reducing infrastructure overbuilding

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Pathways forward

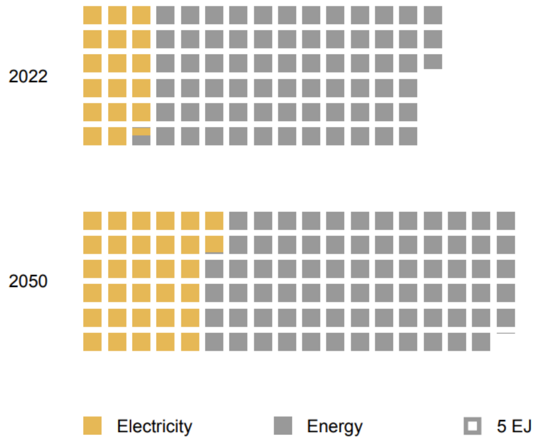
Outlook and implications for growing nuclear capacity

IAEA projections to 2050

IAEA

Energy, Electricity and Nuclear Power Estimates for the Period Up to 2050

RDS-1



- Electricity consumption expected to double by 2050 (+2.4% per year)
- Share of electricity in energy consumption increases by 10%

IAEA projections to 2050

Energy, Electricity and Nuclear Power Estimates for the Period Up to 2050

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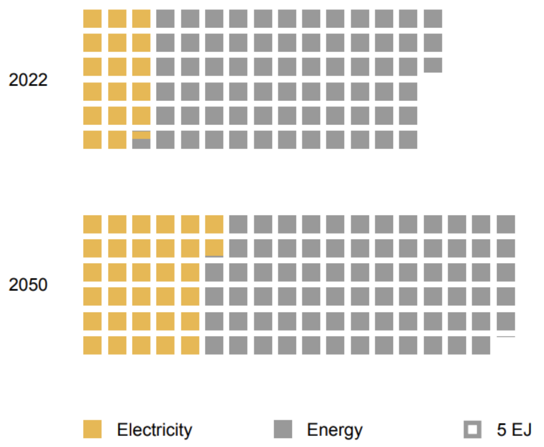

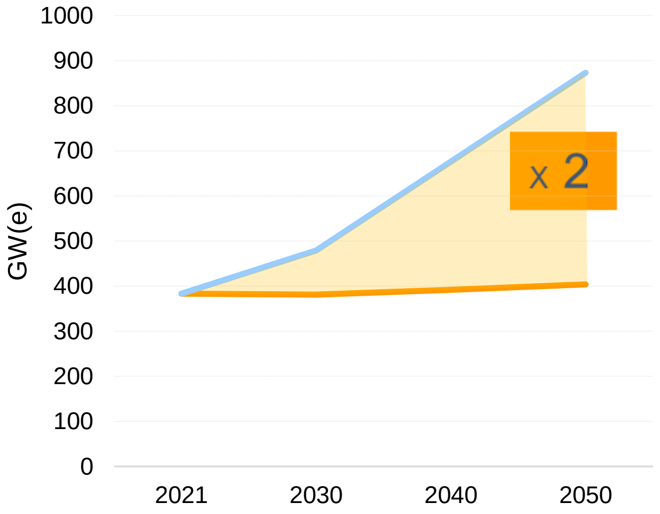

- Electricity consumption expected to double by 2050 (+2.4% per year)
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- High case: **Nuclear capacity increase by 140% by 2050**, nuclear share of total capacity 10%
- Low case: capacity by 2050 increases by 23%, expected capacity share ~7.5%

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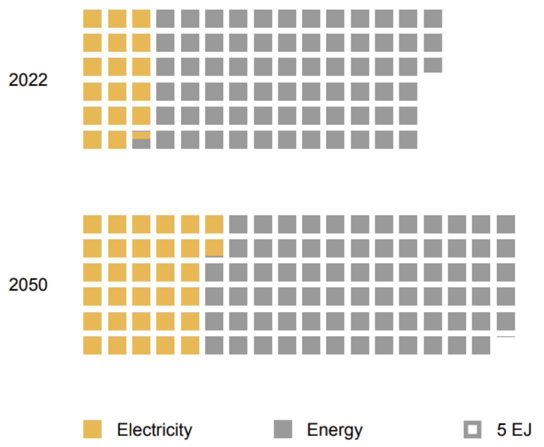

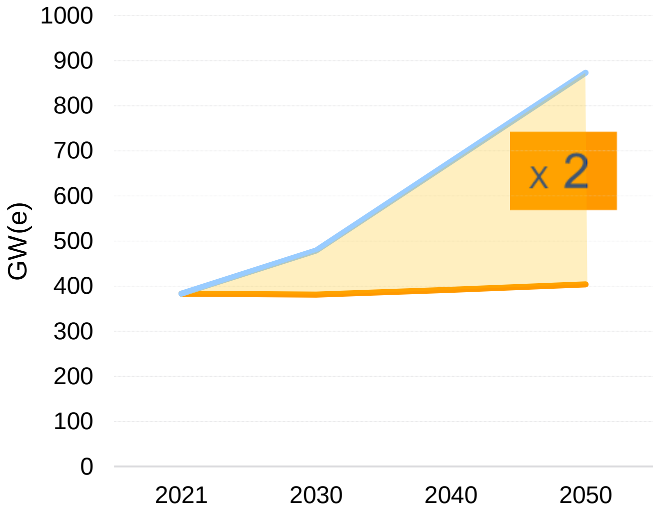

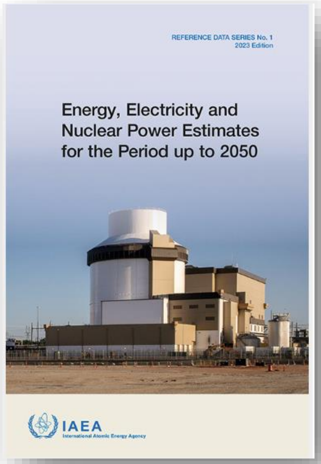

Released Oct. 2023

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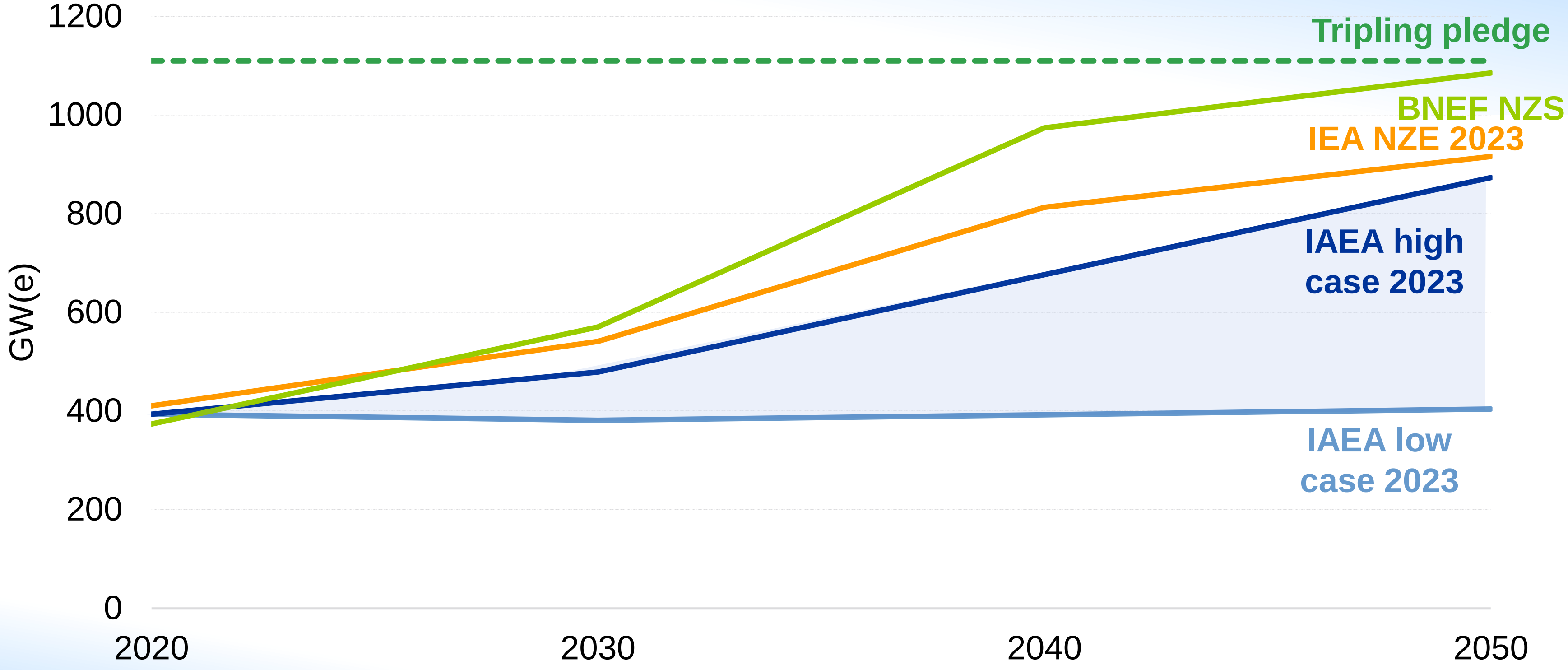
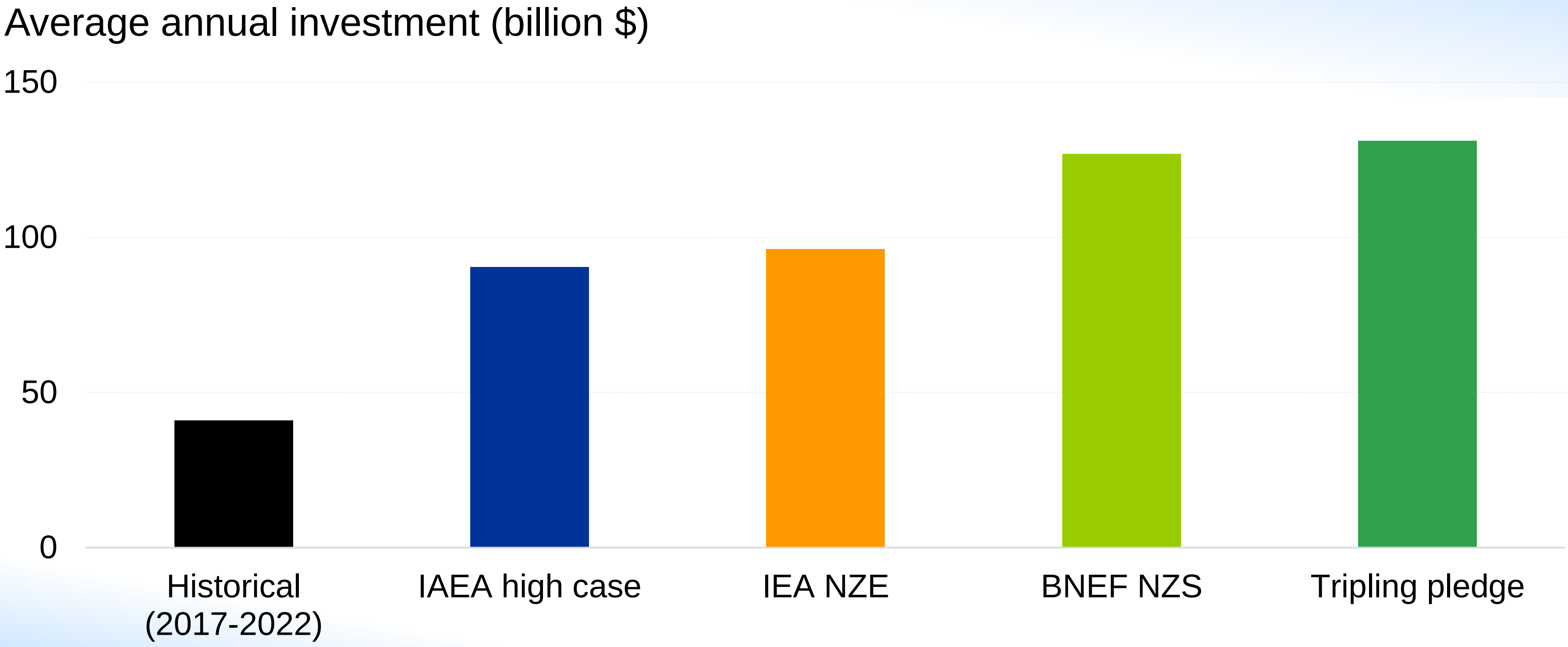
Nuclear capacity projections



Sources: U.S. Department of Energy, BNEF New Energy Outlook 2024, IEA Net Zero Roadmap 2023, IAEA RDS-1 2023

Investment implications



Department of Nuclear Energy
Division of Planning, Information and Knowledge Management
Planning and Economic Studies Section

thank you!

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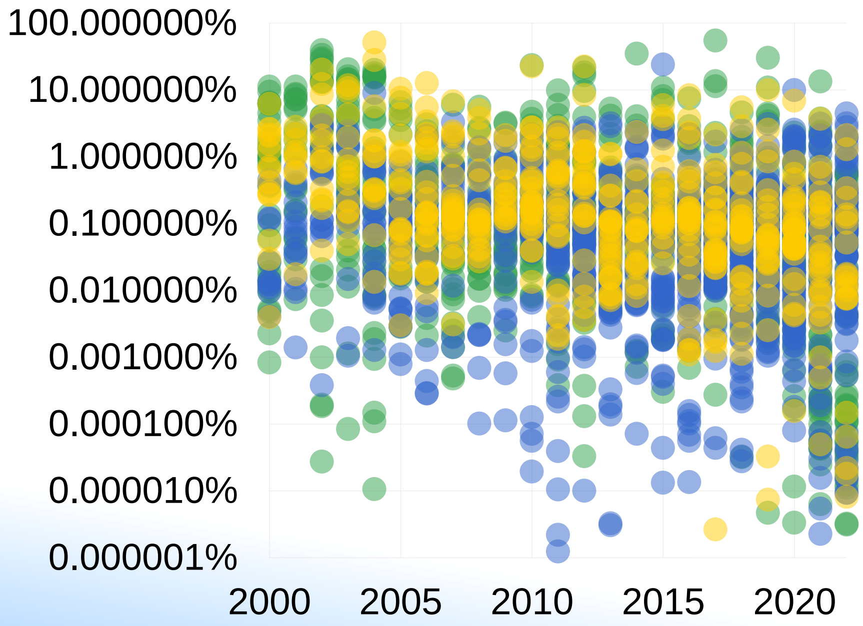
Appendix

Empirical analysis of climate impacts

Testing the historical climate resilience of nuclear power stations

Weather-related nuclear energy losses

As a share of reactor generation



Source: IAEA Power Reactor Information System (PRIS)

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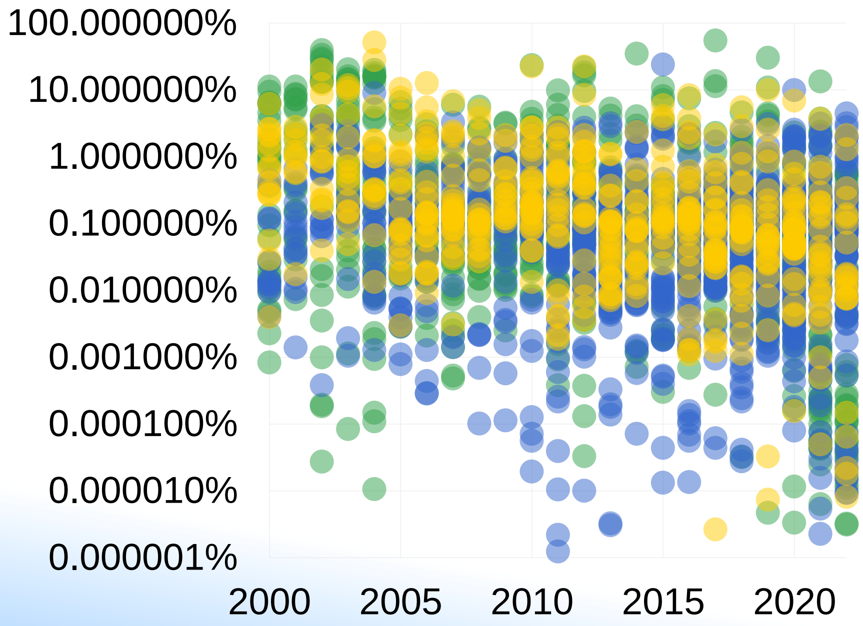
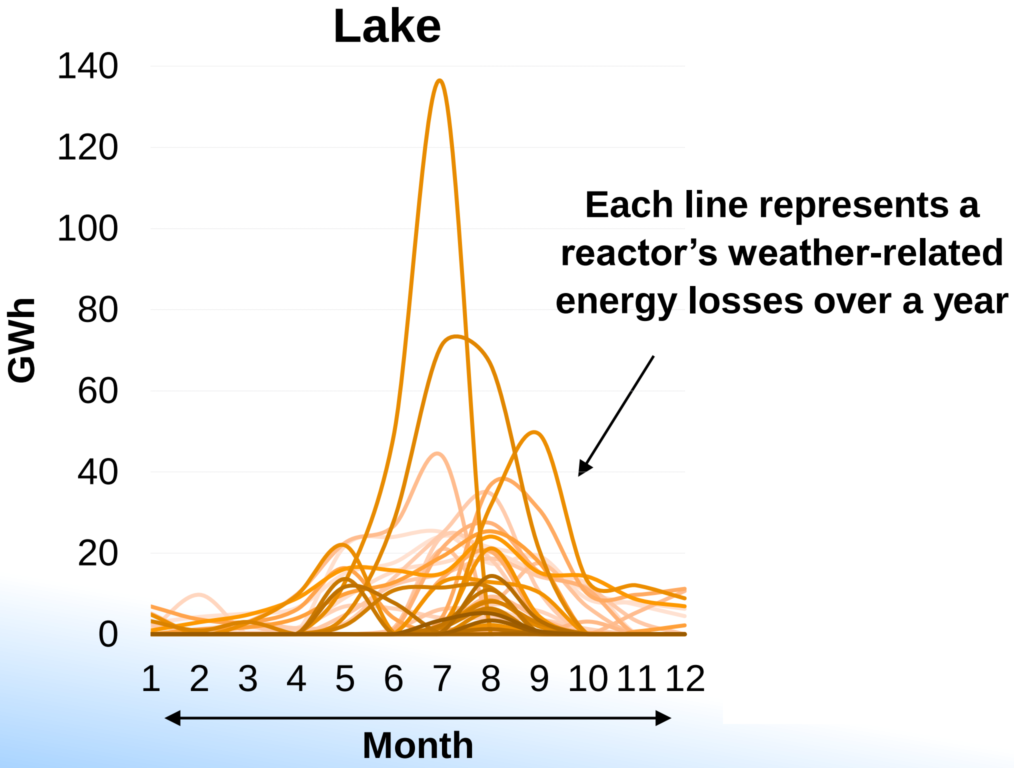


By cooling water type, 2000-2022

Source: IAEA Power Reactor Information System (PRIS)

Monthly weather-related nuclear energy losses by reactor



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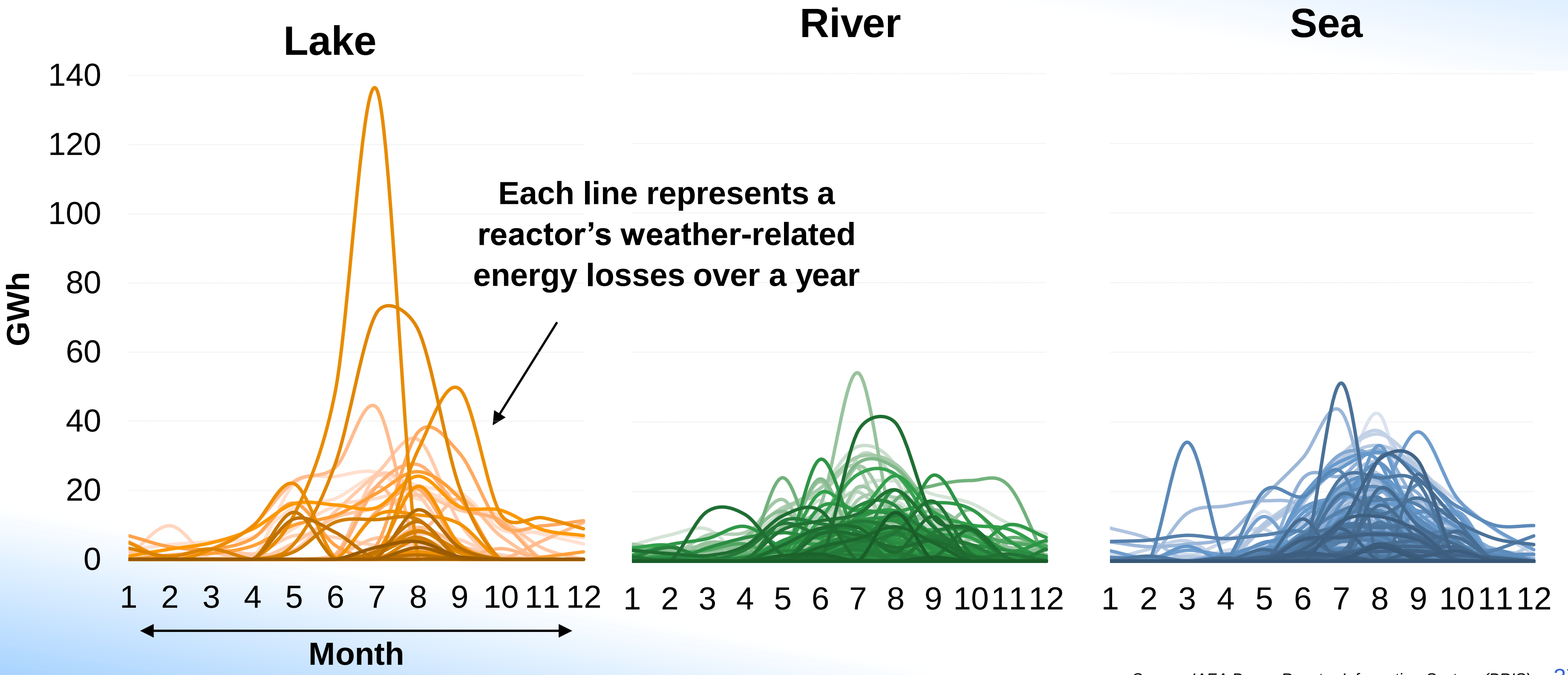

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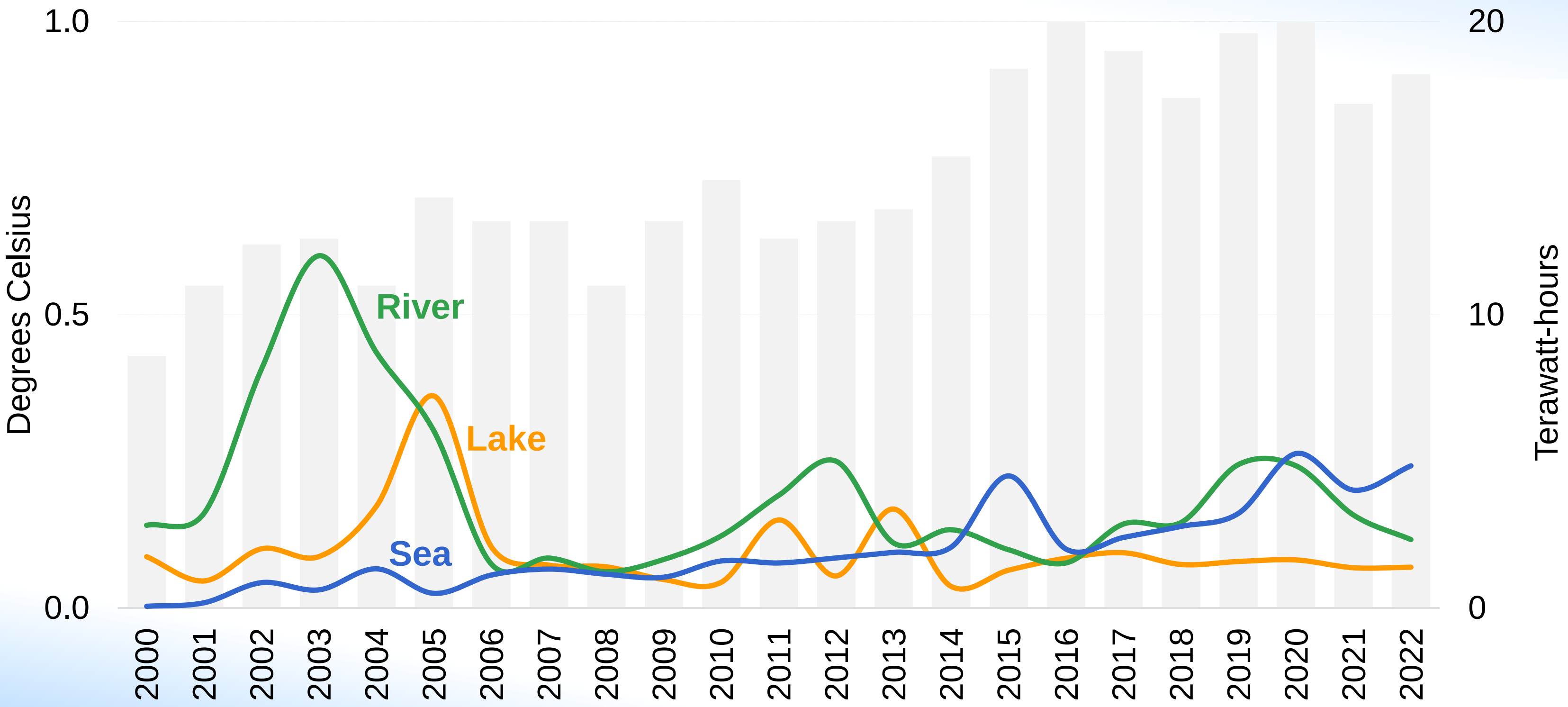
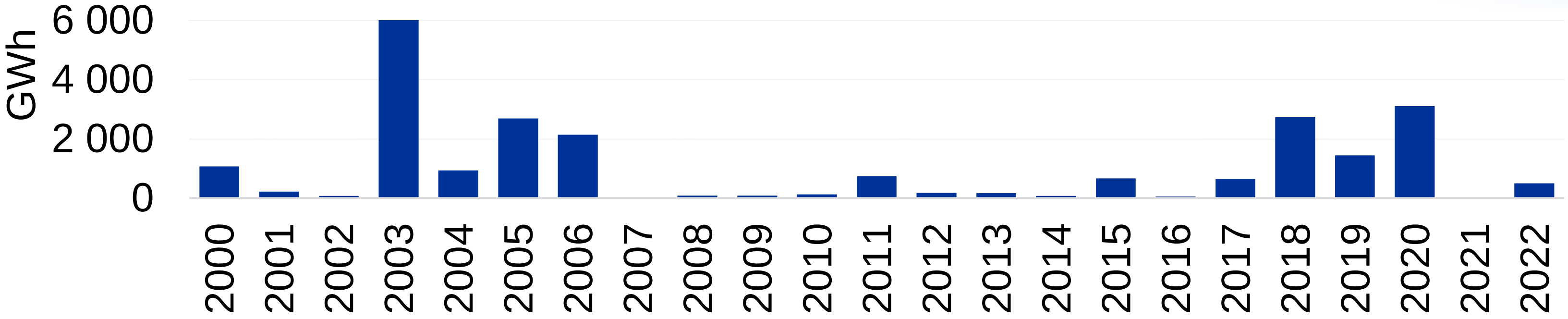


Source: IAEA Power Reactor Information System (PRIS); U.S. National Oceanic and Atmospheric Association (NOAA)

Measuring the Impact of Environmental Conditions on French Nuclear Production

IAEA

Production losses due to thermal environmental regulatory limits by year



Source: Contribution by EDF

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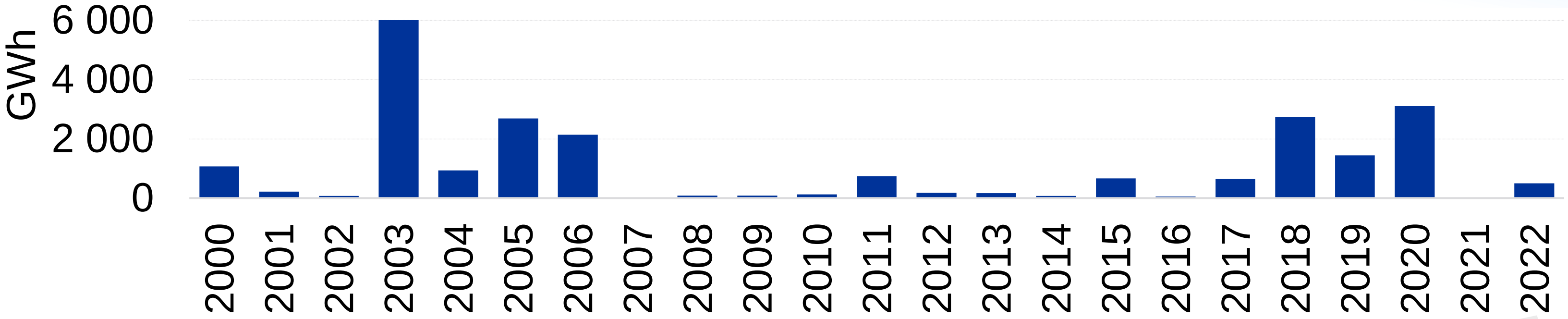
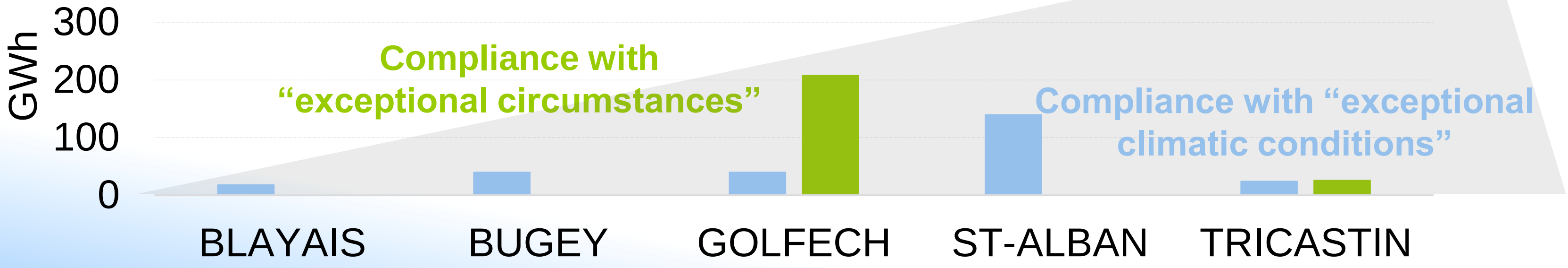


Production losses in 2022 by site



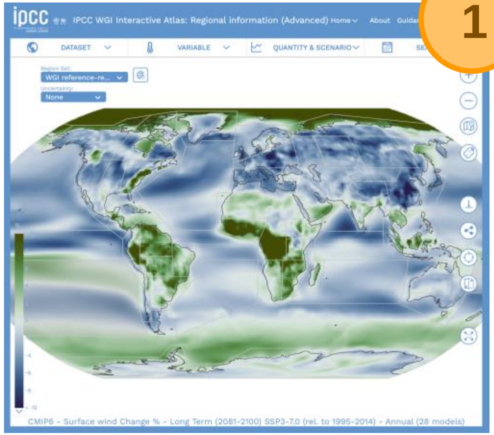
Source: Contribution by EDF

Mapping future infrastructure risks

Overlaying nuclear sites with climate, weather and water risks

IPCC climate projections

1



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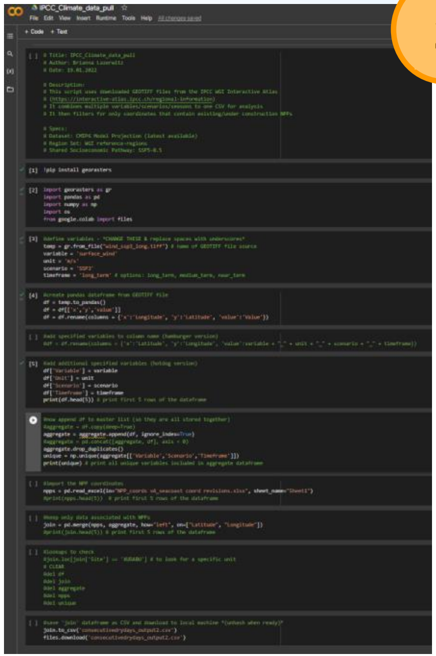
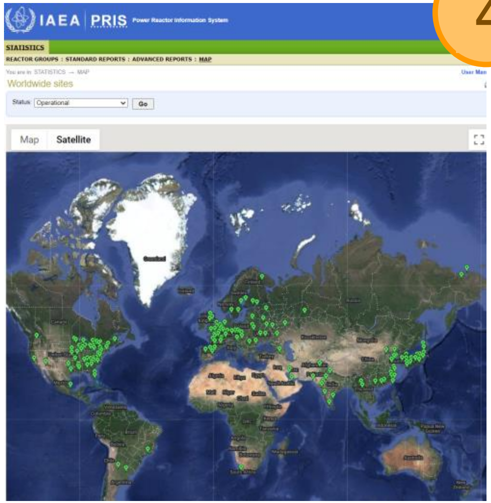


3

	Longitude	Latitude	Value	Variable	Unit	Scenario	Timeframe
0	-180.0	90.0	12.144003	surface_wind	m/s	SSP3	long_term
1	-179.0	90.0	12.143210	surface_wind	m/s	SSP3	long_term
2	-178.0	90.0	12.140996	surface_wind	m/s	SSP3	long_term
3	-177.0	90.0	12.136505	surface_wind	m/s	SSP3	long_term
4	-176.0	90.0	12.131215	surface_wind	m/s	SSP3	long_term

Overlay with NPP site data

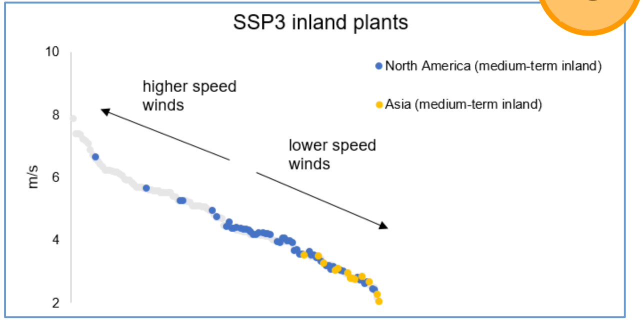
4



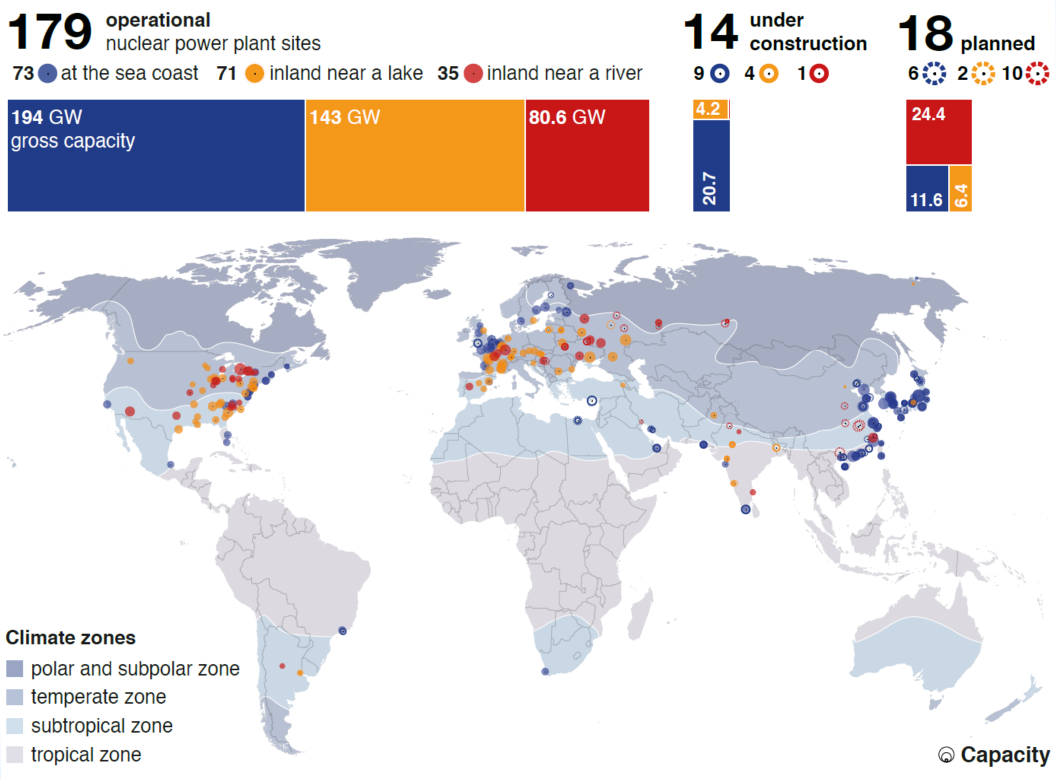
5

Status	Zone	Locatio	Latitude	Longitu	Value	Variable	Unit	Scenari	Tim
Operation	Mild Temp	Inland nea	39.80806	-5.69694	3.118247	surface_w	ms*-1	SSP1	near_
Operation	Mild Temp	Inland nea	39.80806	-5.69694	3.112548	surface_w	ms*-1	SSP1	medium
Operation	Mild Temp	Inland nea	39.80806	-5.69694	3.147132	surface_w	ms*-1	SSP1	long_term
Operation	Mild Temp	Inland nea	39.80806	-5.69694	3.007348	surface_w	ms*-1	SSP2	long_term
Operation	Mild Temp	Inland nea	39.80806	-5.69694	3.023111	surface_w	ms*-1	SSP2	medium_t
Operation	Mild Temp	Inland nea	39.80806	-5.69694	3.02984	surface_w	ms*-1	SSP2	near_term
Operation	Mild Temp	Inland nea	39.80806	-5.69694	3.138797	surface_w	ms*-1	SSP3	near_term
Operation	Mild Temp	Inland nea	39.80806	-5.69694	3.120813	surface_w	ms*-1	SSP3	medium_t
Operation	Mild Temp	Inland nea	39.80806	-5.69694	3.085675	surface_w	ms*-1	SSP3	long_term
Operation	Sub Tropic	Sea Coast	-23.0083	-44.4569	4.640002	surface_w	ms*-1	SSP1	near_term
Operation	Sub Tropic	Sea Coast	-23.0083	-44.4569	4.652218	surface_w	ms*-1	SSP1	medium_t
Operation	Sub Tropic	Sea Coast	-23.0083	-44.4569	4.652304	surface_w	ms*-1	SSP1	long_term
Operation	Sub Tropic	Sea Coast	-23.0083	-44.4569	4.757503	surface_w	ms*-1	SSP2	long_term
Operation	Sub Tropic	Sea Coast	-23.0083	-44.4569	4.747385	surface_w	ms*-1	SSP2	medium_t
Operation	Sub Tropic	Sea Coast	-23.0083	-44.4569	4.724737	surface_w	ms*-1	SSP2	near_term
Operation	Sub Tropic	Sea Coast	-23.0083	-44.4569	4.590316	surface_w	ms*-1	SSP3	near_term
Operation	Sub Tropic	Sea Coast	-23.0083	-44.4569	4.616025	surface_w	ms*-1	SSP3	medium_t
Operation	Sub Tropic	Sea Coast	-23.0083	-44.4569	4.6656	surface_w	ms*-1	SSP3	long_term
Operation	Sub Tropic	Sea Coast	-23.0069	-44.4628	4.640002	surface_w	ms*-1	SSP1	near_term
Operation	Sub Tropic	Sea Coast	-23.0069	-44.4628	4.652218	surface_w	ms*-1	SSP1	medium_t
Operation	Sub Tropic	Sea Coast	-23.0069	-44.4628	4.652304	surface_w	ms*-1	SSP1	long_term
Operation	Sub Tropic	Sea Coast	-23.0069	-44.4628	4.757503	surface_w	ms*-1	SSP2	long_term
Operation	Sub Tropic	Sea Coast	-23.0069	-44.4628	4.747385	surface_w	ms*-1	SSP2	medium_t
Operation	Sub Tropic	Sea Coast	-23.0069	-44.4628	4.724737	surface_w	ms*-1	SSP2	near_term
Operation	Sub Tropic	Sea Coast	-23.0069	-44.4628	4.590316	surface_w	ms*-1	SSP3	near_term
Operation	Sub Tropic	Sea Coast	-23.0069	-44.4628	4.616025	surface_w	ms*-1	SSP3	medium_t
Operation	Sub Tropic	Sea Coast	-23.0069	-44.4628	4.6656	surface_w	ms*-1	SSP3	long_term
Operation	Mild Temp	Inland nea	35.22667	-93.2308	2.95865	surface_w	ms*-1	SSP1	near_term
Operation	Mild Temp	Inland nea	35.22667	-93.2308	2.919417	surface_w	ms*-1	SSP1	medium_t
Operation	Mild Temp	Inland nea	35.22667	-93.2308	2.908994	surface_w	ms*-1	SSP1	long_term
Operation	Mild Temp	Inland nea	35.22667	-93.2308	2.942616	surface_w	ms*-1	SSP2	long_term
Operation	Mild Temp	Inland nea	35.22667	-93.2308	2.984007	surface_w	ms*-1	SSP2	medium_t
Operation	Mild Temp	Inland nea	35.22667	-93.2308	3.018827	surface_w	ms*-1	SSP2	near_term
Operation	Mild Temp	Inland nea	35.22667	-93.2308	3.017048	surface_w	ms*-1	SSP3	near_term
Operation	Mild Temp	Inland nea	35.22667	-93.2308	3.011183	surface_w	ms*-1	SSP3	medium_t

6



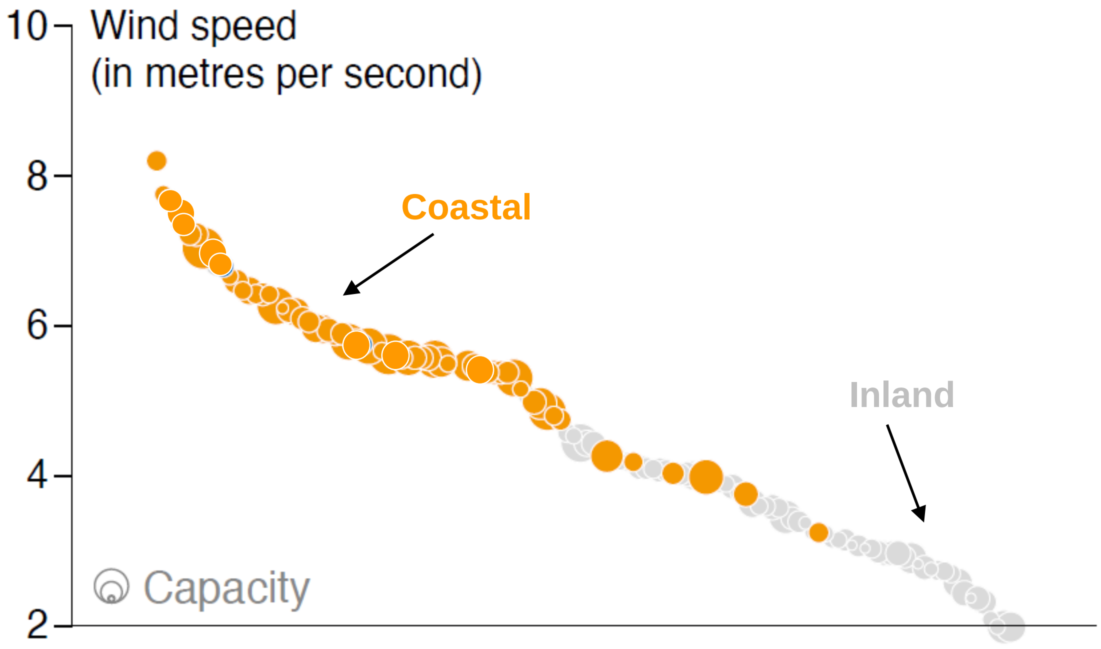
Location of nuclear sites



Source: *IAEA PRIS. Note: each bubble represents an operational, under construction or planned nuclear site. Nuclear sites increasing their capacities with additional reactors are counted as a single plant site. The contours of climatic zones are indicative; their borders are likely to evolve with the changing global climate.*

Projected high wind speeds

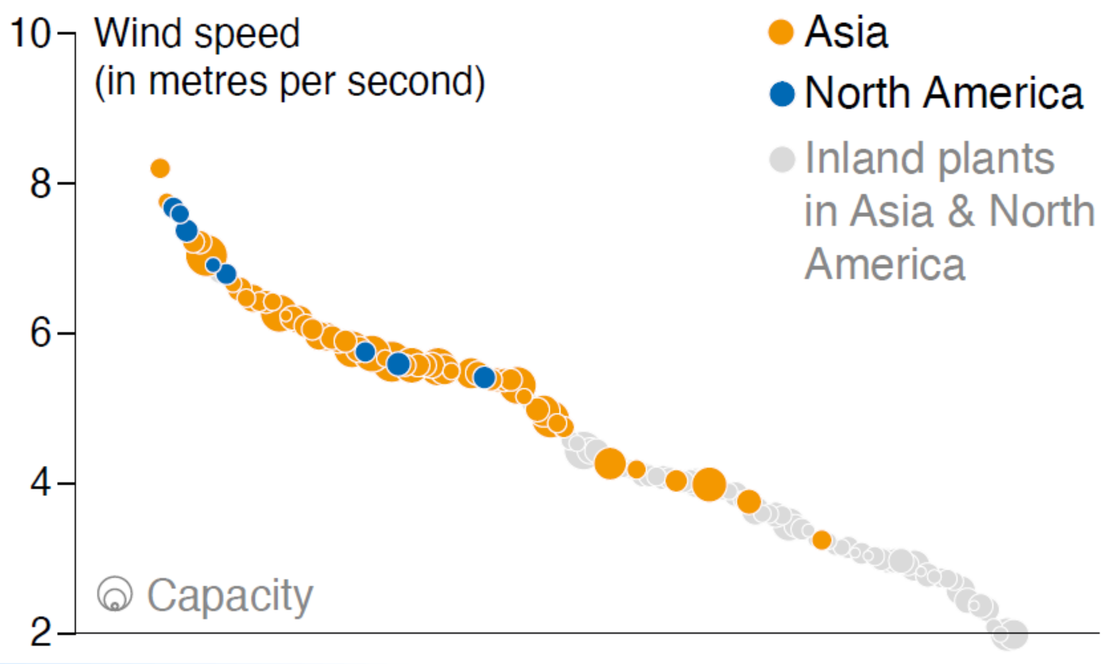
Coastal sites experience higher winds than inland sites



Source: based on climate data from IPCC and nuclear data from IAEA PRIS. Note: Average wind speeds do not vary vastly across SSP storylines and time frames, hence the choice of the intermediate SSP2 case in the medium term (2041-2060) for illustration purposes.

Projected high wind speeds

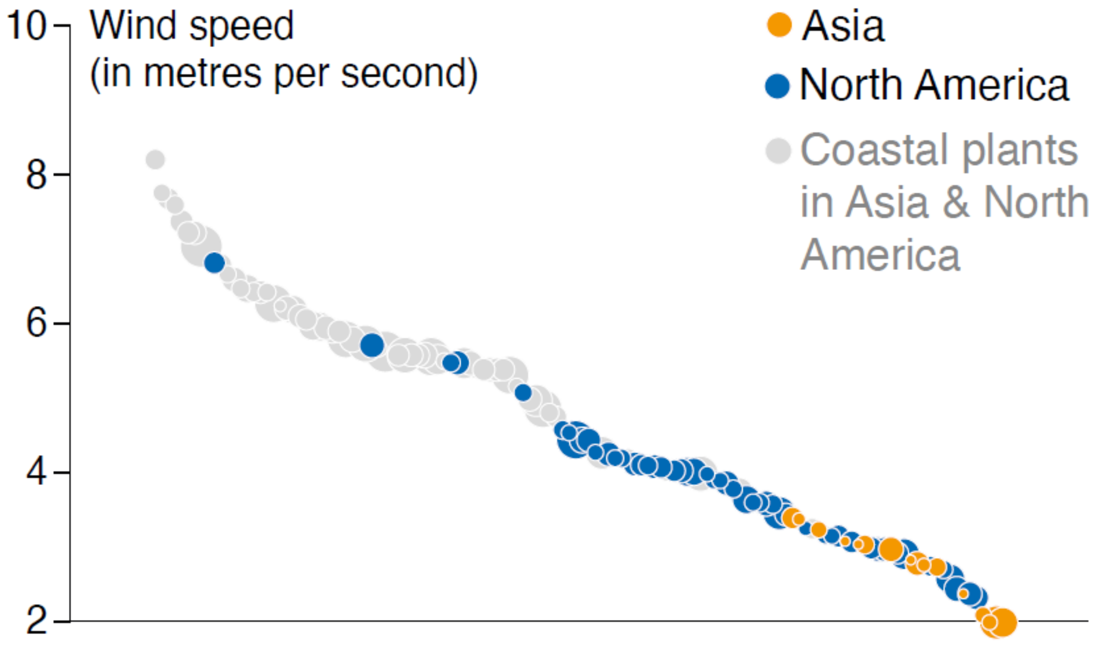
Nuclear sites in Asia are concentrated on the coast



Source: based on climate data from IPCC and nuclear data from IAEA PRIS. Note: Average wind speeds do not vary vastly across SSP storylines and time frames, hence the choice of the intermediate SSP2 case in the medium term (2041-2060) for illustration purposes.

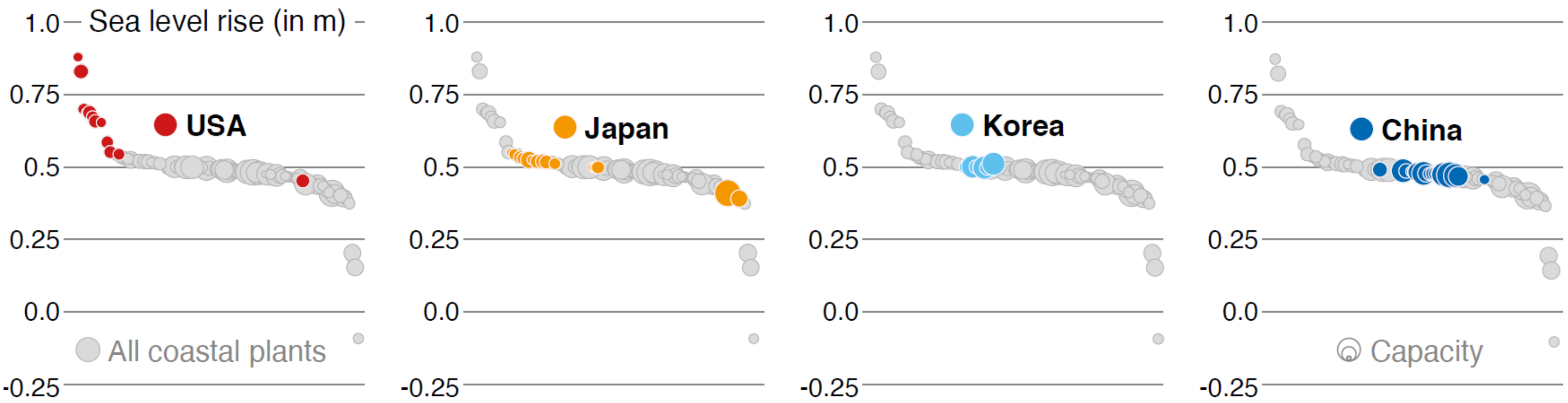
Projected high wind speeds

Nuclear sites in North America are concentrated inland



Source: based on climate data from IPCC and nuclear data from IAEA PRIS. Note: Average wind speeds do not vary vastly across SSP storylines and time frames, hence the choice of the intermediate SSP2 case in the medium term (2041-2060) for illustration purposes.

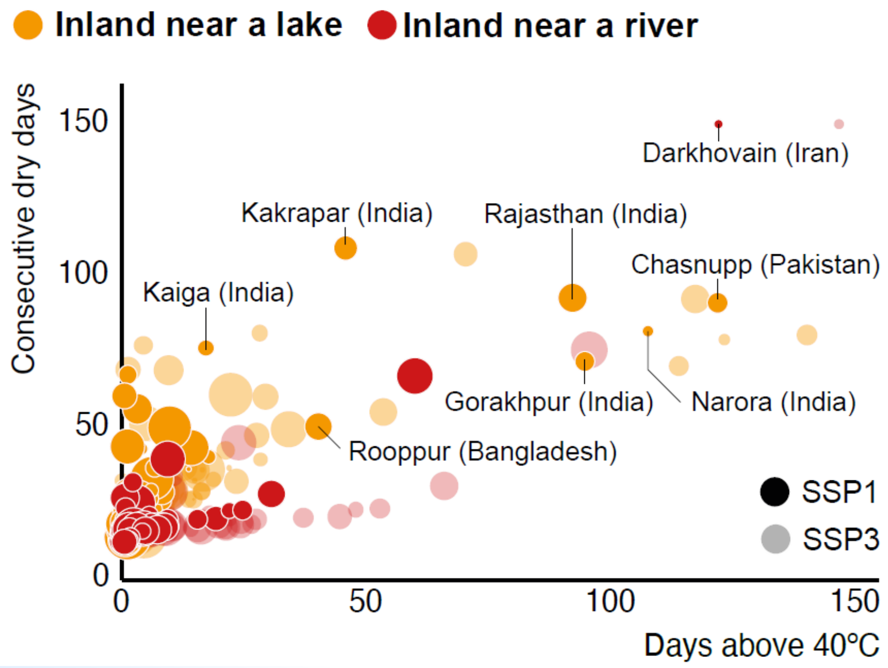
Projected sea level rise



Source: based on climate data from IPCC and nuclear data from IAEA PRIS. Charts represent change between near (2021-2040) and long term (2081-2100) under the SSP3 scenario by country.

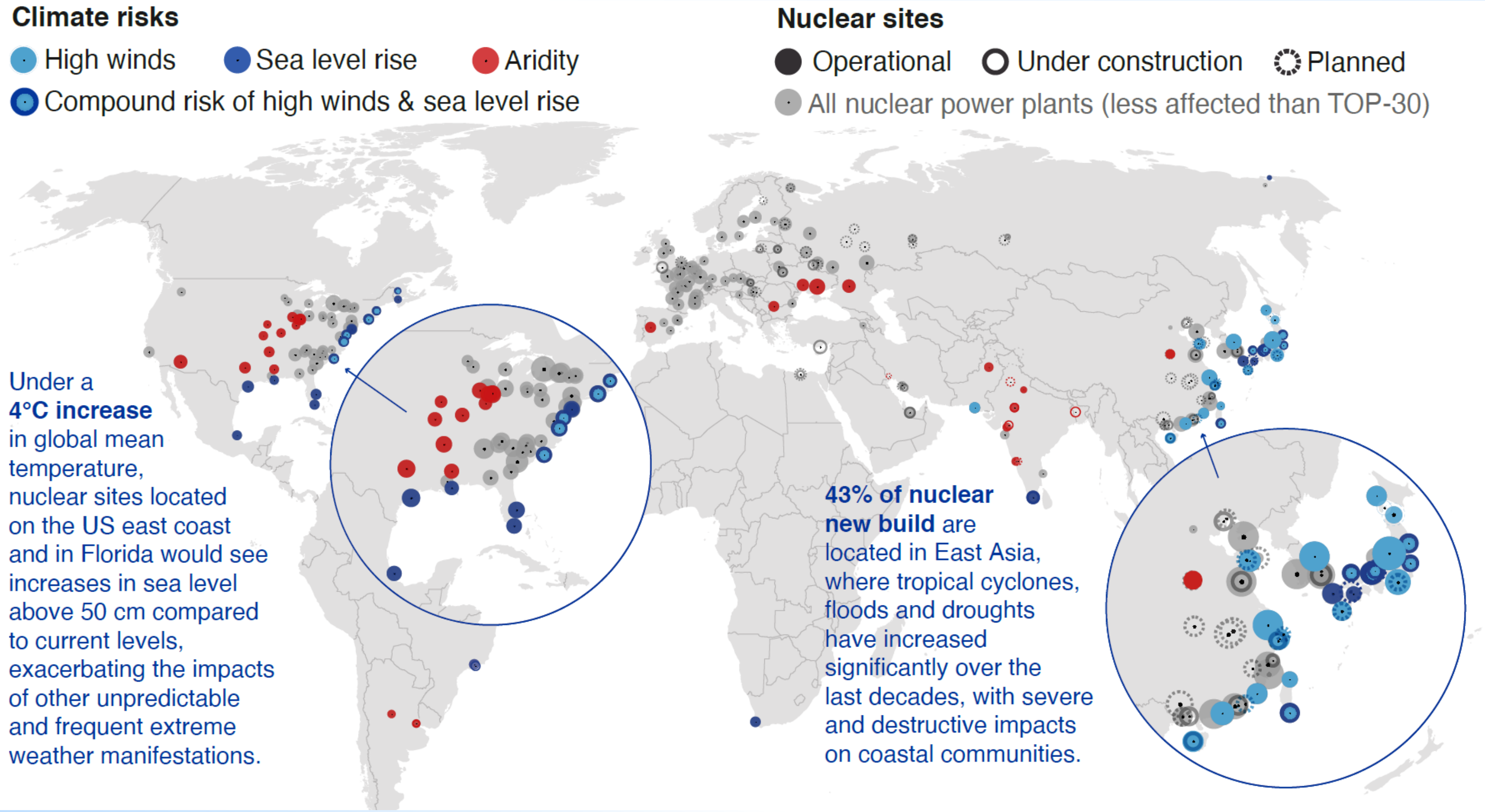
Projected heat and aridity risks

Inland nuclear site exposure to extreme heat and aridity in the long term (2081-2100) in SSP1 and SSP3 scenarios



Source: based on climate data from IPCC and nuclear data from IAEA PRIS.

Global overview

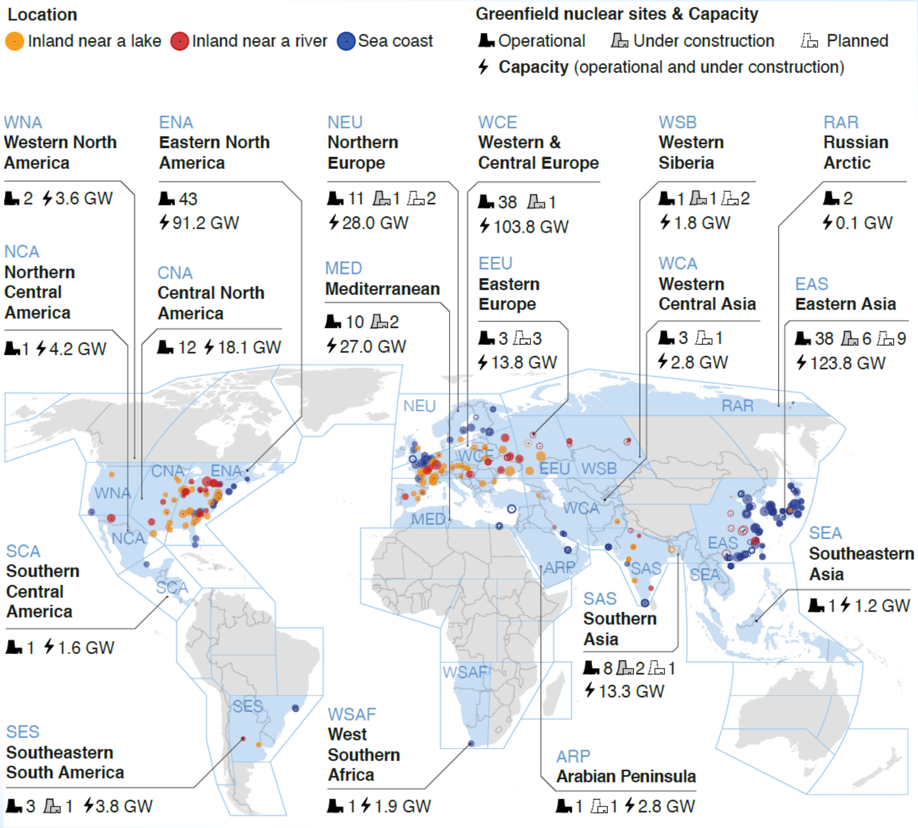


Under a **4°C increase** in global mean temperature, nuclear sites located on the US east coast and in Florida would see increases in sea level above 50 cm compared to current levels, exacerbating the impacts of other unpredictable and frequent extreme weather manifestations.

43% of nuclear new build are located in East Asia, where tropical cyclones, floods and droughts have increased significantly over the last decades, with severe and destructive impacts on coastal communities.

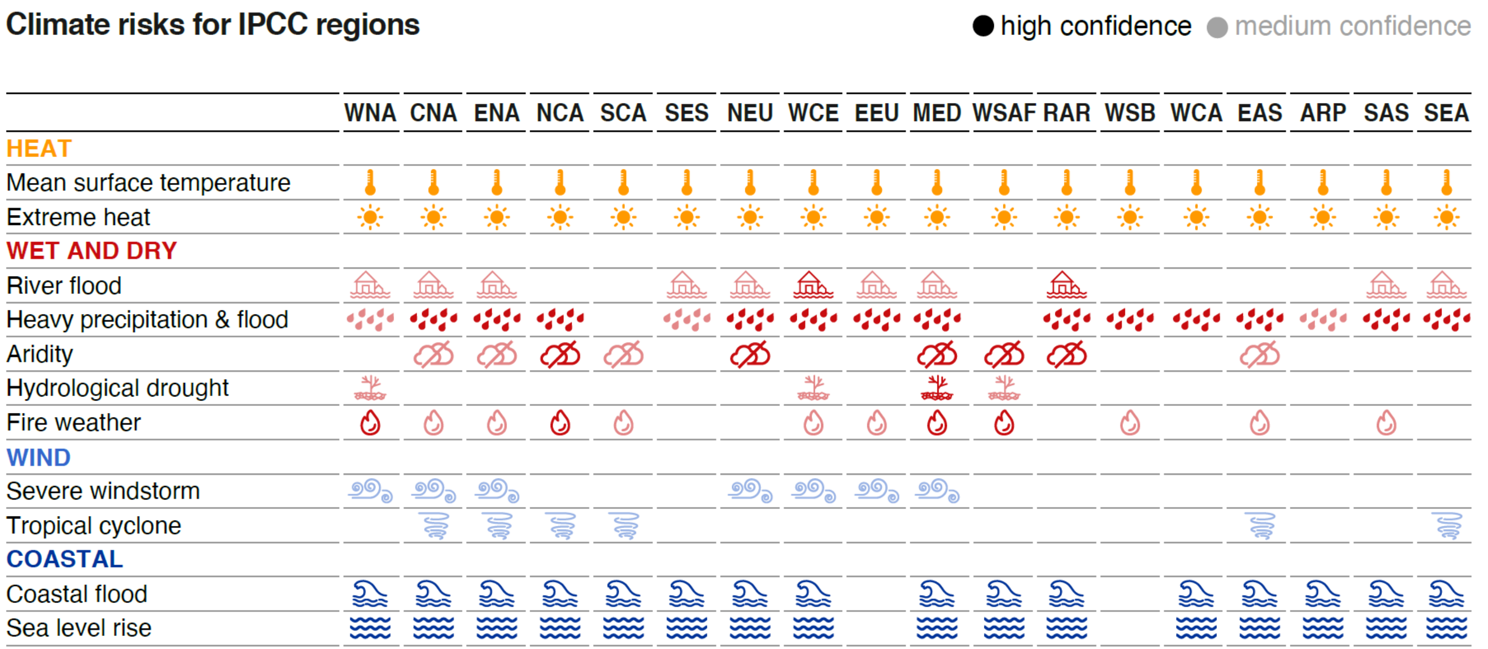
Source: based on climate data from IPCC and nuclear data from IAEA PRIS.

Regional climate risks



Source: based on climate data from IPCC and nuclear data from IAEA PRIS. Note: nuclear sites increasing their capacities with additional reactors are counted as a single plant site.

Regional climatic impact drivers



Source: IPCC

International Atomic Energy Agency
Atoms for Peace and Development

The IAEA's Power Reactor Information System (PRIS)

Variables included in the dataset, limitations and opportunities

2023 PRIS reactor status

IAEA

Reactors in operation**

393.8 GW(e) total net capacity

438 reactors

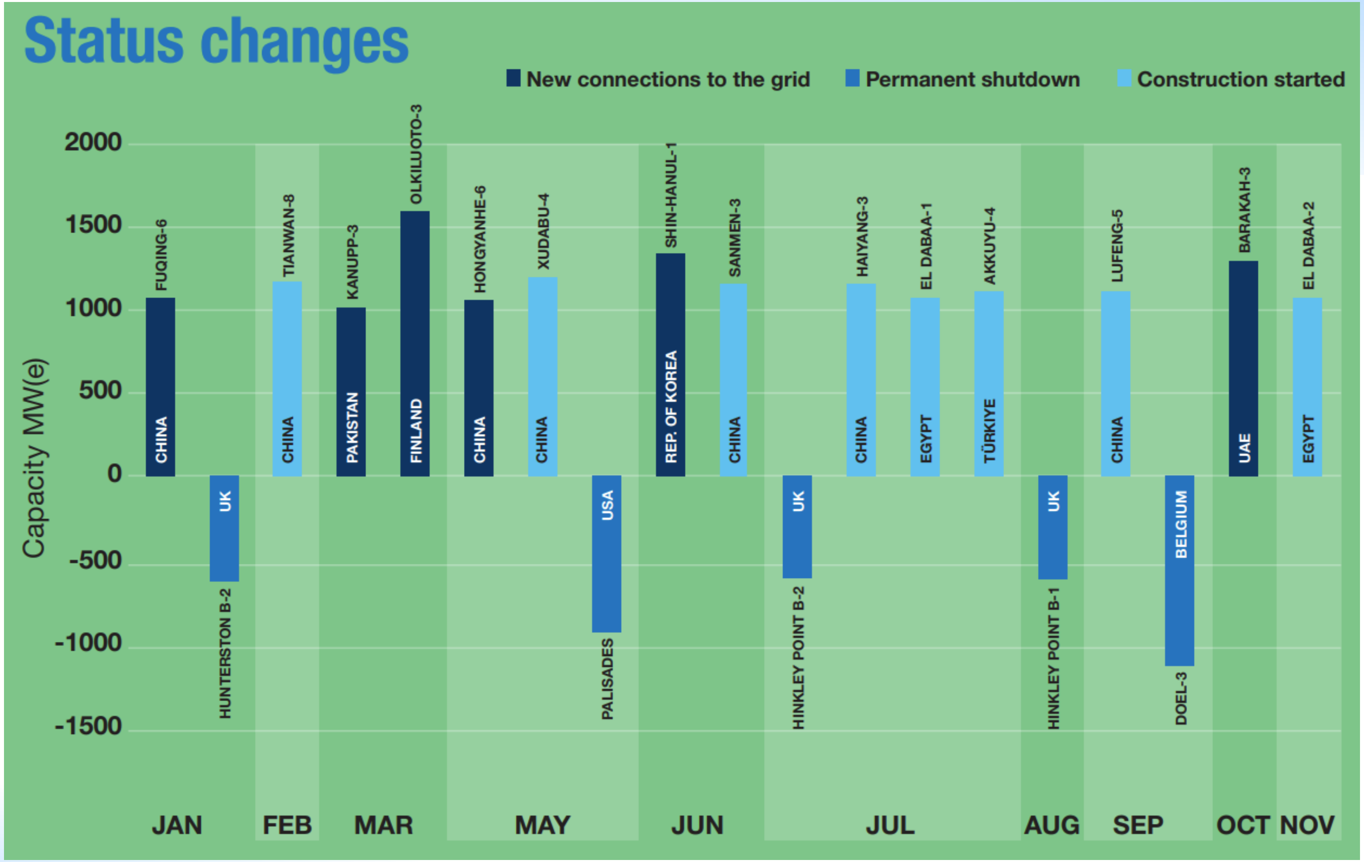
Reactors under construction

59.3 GW(e) total net capacity

58 reactors

Operating experience

19 764 reactor-years of operation (cumulative)



Source: IAEA PRIS

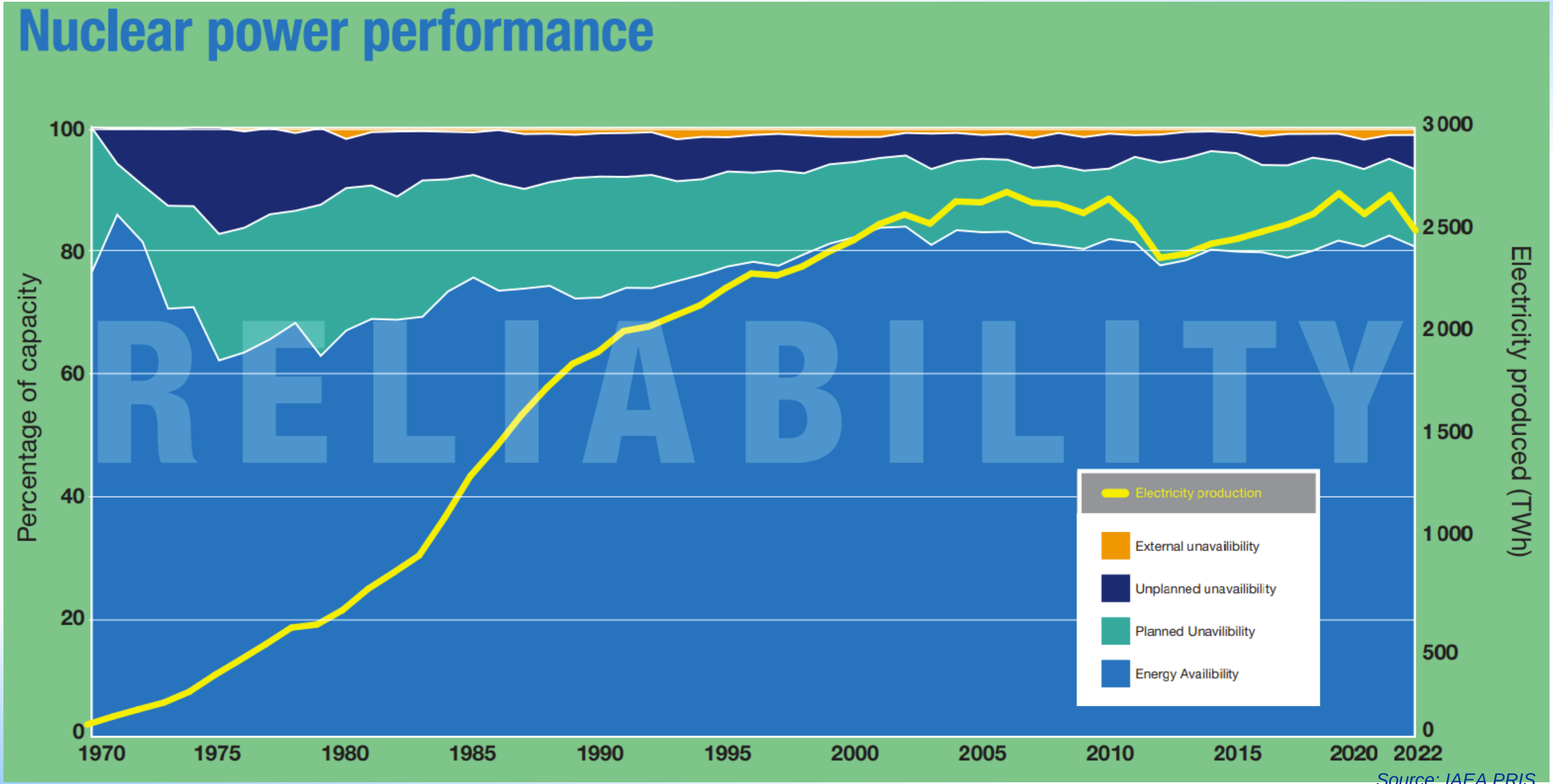
Country statistics

Country	Reactors in operation	Net capacity (MW(e))	Reactors under construction	Net capacity (MW(e))	Nuclear share	Electricity produced (TWh)
Argentina	3	1641	1	25	5.4%	7.5
Armenia	1	416	0	0	31.0%	2.6
Bangladesh	0	0	2	2160	NA	NA
Belarus	1	1110	1	1110	11.9%	4.4
Belgium	6	4936	0	0	46.4%	41.7
Egypt	0	0	2	2200	NA	NA
Finland	5	4394	0	0	35.0%	24.2
France	56	61370	1	1630	62.6%	282.1
Germany	3	4055	0	0	5.8%	31.9
Hungary	4	1916	0	0	47.0%	15.0
Netherlands	1	482	0	0	3.3%	3.9
Pakistan	6	3262	0	0	16.2%	22.2
Romania	2	1300	0	0	19.3%	10.2
Russia	37	27727	3	2700	19.6%	209.5
Slovakia	4	1868	2	880	59.2%	14.6
Brazil	2	1884	1	1340	2.5%	13.7
Bulgaria	2	2006	0	0	32.5%	15.8
Canada	19	13624	0	0	12.9%	81.7
China	54	52181	20	20284	5.0%	395.4
Czech Republic	6	3934	0	0	36.7%	29.3
India	19	6290	8	6028	3.1%	42.0
Islamic Republic of Iran	1	915	1	974	1.7%	6.0
Japan	10	9486	2	2653	6.1%	51.9
Republic of Korea	25	24489	3	4020	30.4%	167.5
Mexico	2	1552	0	0	4.5%	10.5
Slovenia	1	688	0	0	42.8%	5.3
South Africa	2	1854	0	0	4.9%	10.1
Spain	7	7123	0	0	20.3%	56.2
Sweden	6	6937	0	0	29.5%	50.0
Switzerland	4	2973	0	0	36.4%	23.2
United Kingdom	9	5883	2	3260	14.2%	43.6
United States	92	94718	2	2234	18.2%	772.2
Türkiye	0	0	4	4456	NA	NA
Ukraine	15	13107	2	2070	*	*
United Arab Emirates	3	4011	1	1310	12.3%	19.3

Reactors in operation · Reactors under construction · Net capacity (MW(e)) · Electricity produced (TWh) · % Nuclear share

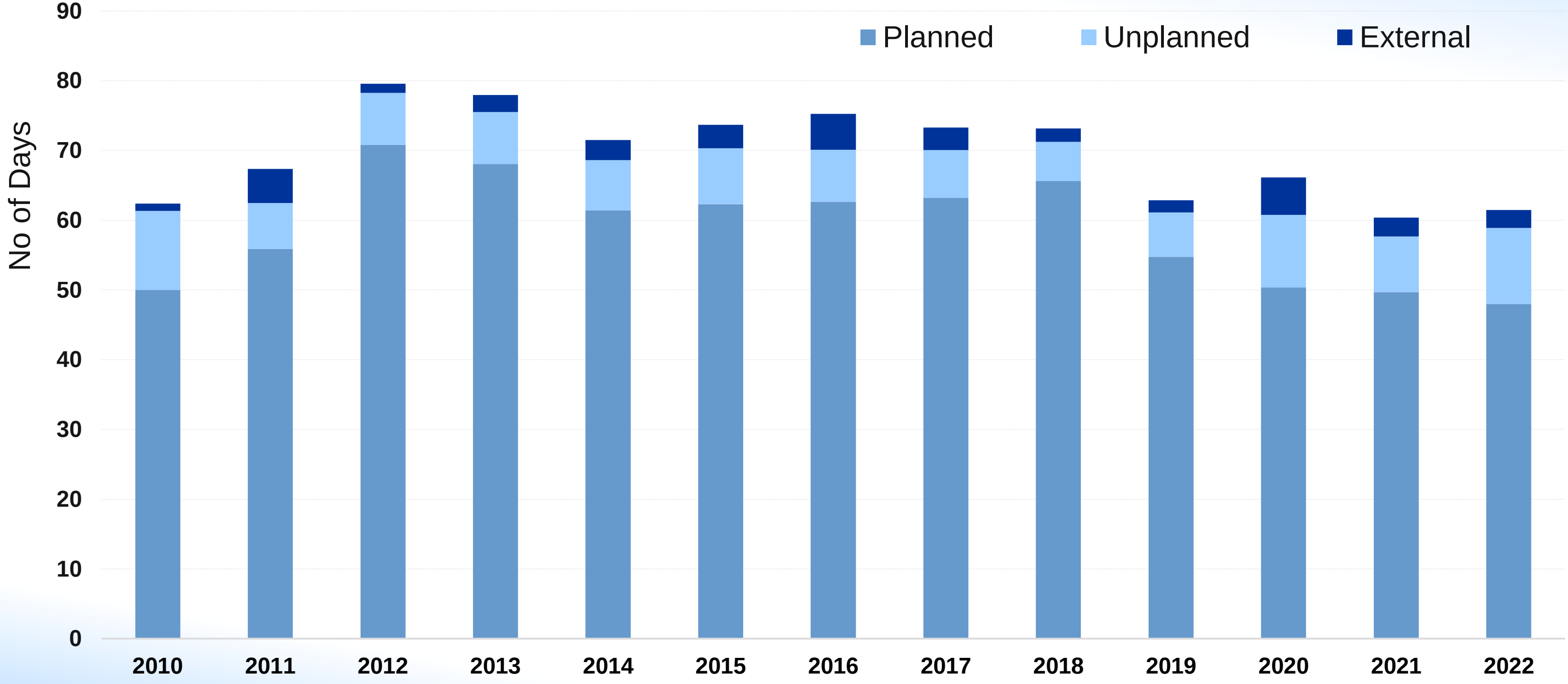
Source: IAEA PRIS

2023 PRIS update



Source: IAEA PRIS

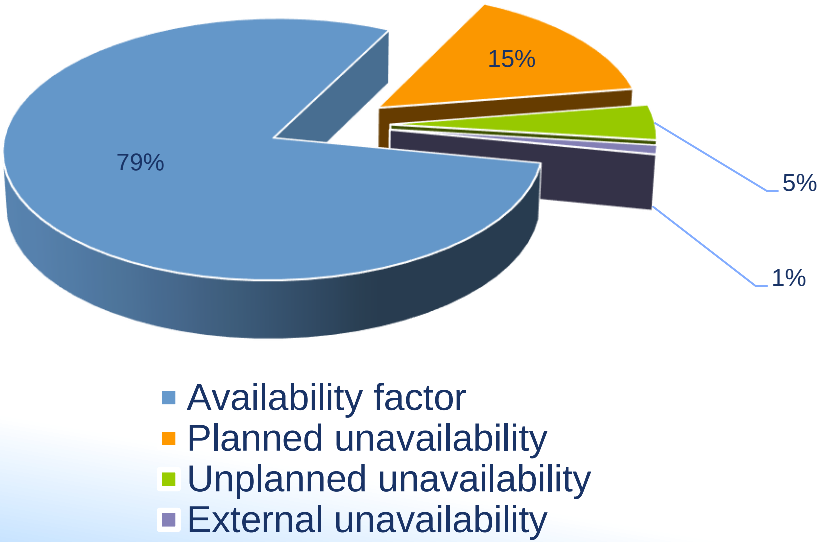
Planned and Unplanned Outages



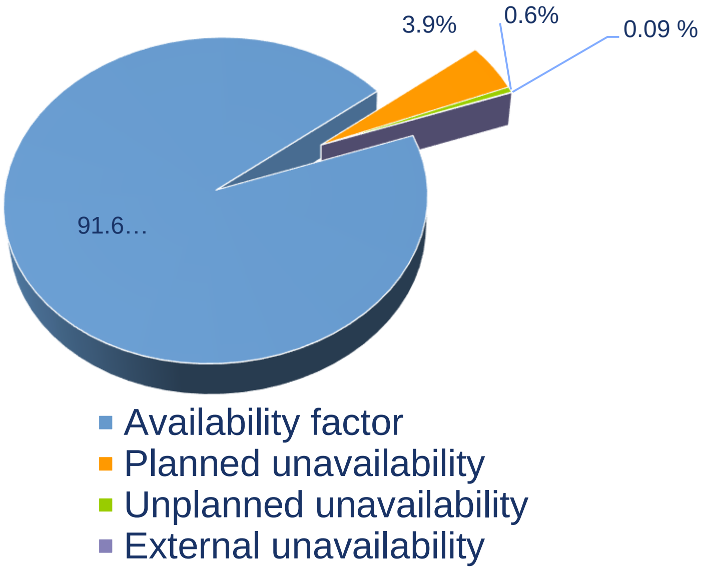
Source: IAEA PRIS

Energy losses in PRIS (2004-2022)

All nuclear power reactors



Best performing reactors



Source: IAEA PRIS

Data limitations and opportunities

- Data represented in the database are subject to availability and reporting by IAEA Member States
- The management of the PRIS database is an iterative process between end users and data providers to balance reporting obligations with useful and necessary data for analysis
- “Living database” – constant improvement of user interface and data collection