Climate change vulnerability and adaptation in the energy sector, focus on the nuclear power sector

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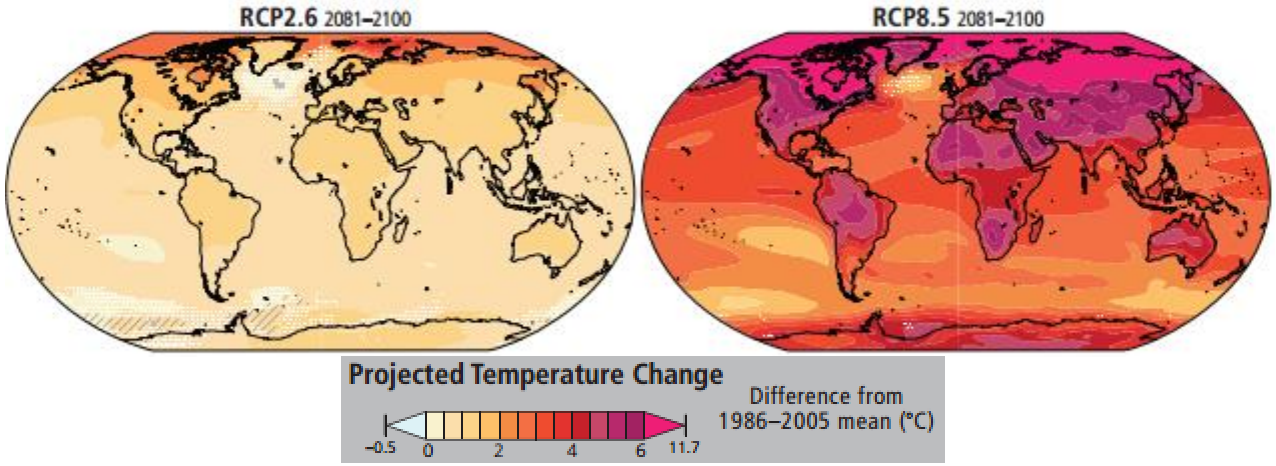
OECD Nuclear Energy Agency (NEA) and the International Atomic Energy Agency (IAEA)
COP21, Thursday, 10 December 2015

Climate Change (CC) and Extreme Weather (EW)

- **Gradual change:** *Changes in mean and variability over decades*
  - Temperature
  - Precipitation
  - Wind patterns
  - Insolation
  - Sea level rise



- **Extreme events:** *Occurrence above or below threshold, near to boundaries of observed values*
  - Heat waves, heavy precipitation, drought, high winds/storms, etc…
  - Increasing frequency and intensity, affecting larger areas, prevailing longer

Source: Derived from IPCC

Mitigation and adaptation

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Much research has been done on how to mitigate climate change (CC) through changes in the energy system

- Few studies have evaluated the reverse: the impact of CC and extreme weather (EW) on energy infrastructure
- Expectations are that regardless of mitigation action now, there will be a certain level of CC (IPCC AR5 WGI)

⇒ identify the impacts of CC and EW and adapt to lessen those impacts

Impacts on energy infrastructure

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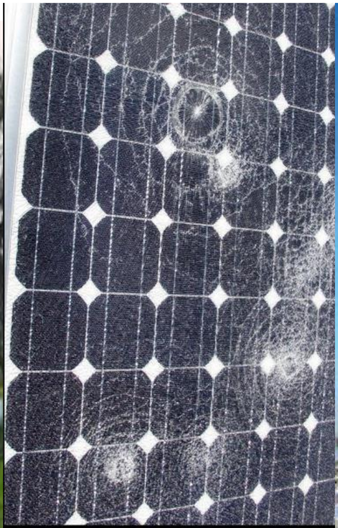
Extraction/Resource → Transport → Conversion → Transmission & Distribution

IAEA activities

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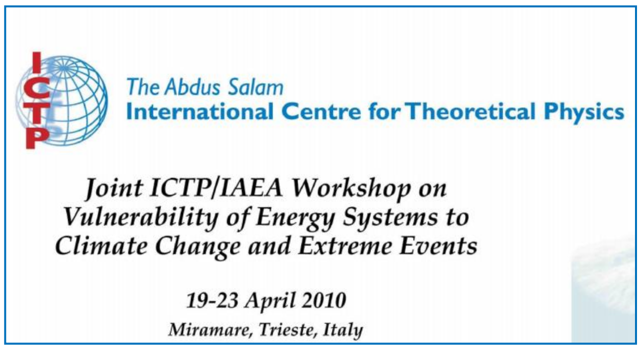
IAEA workshop organised in 2010

⇒ Raised interest in Member States

⇒ Results published in *Climatic Change*



Ongoing study: *Adaptation of nuclear and non-nuclear energy infrastructure*

- Techno-economic evaluation
- Long-term climate change / Extreme weather
- Country case studies: Argentina, Cuba, China, Egypt, Ghana, Pakistan, Slovenia

CRP Case study: Argentina

- Observed climate trends and regional projections for CC ➡ main vulnerabilities presenting potential hazards for the electricity system.

Major vulnerability

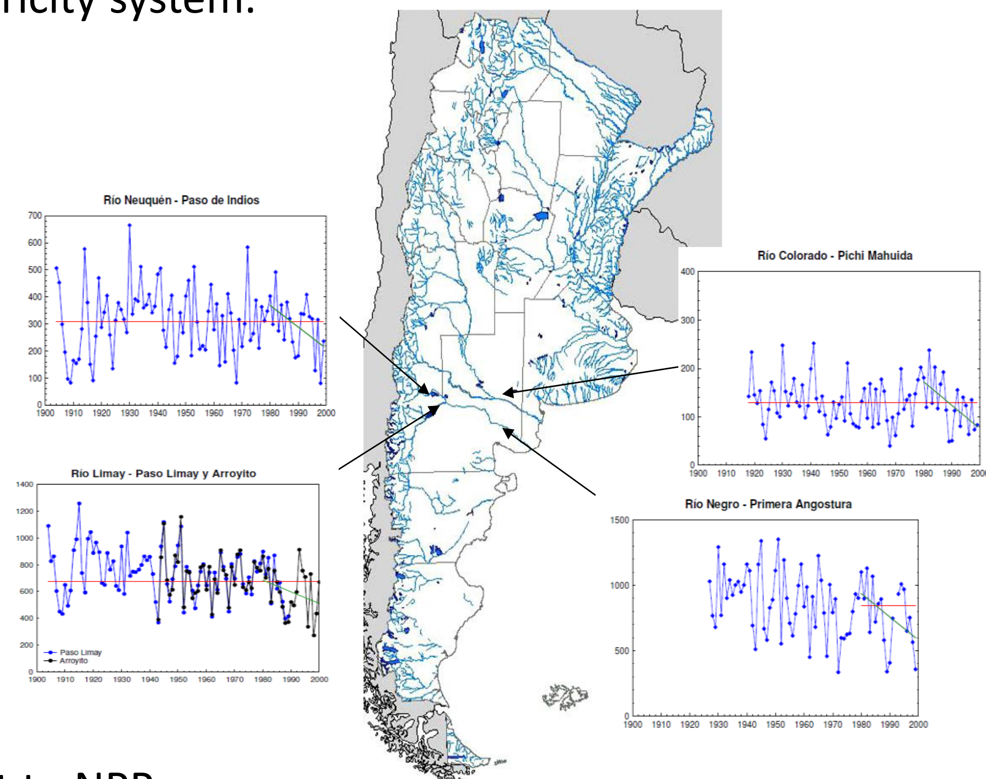
⇒ Decrease in rainfall / streamflow of the rivers in the regions of Cuyo and Comahue

⇒ Home to ~ 52% of the country's hydropower plants (HPPs) capacity (> 18% of the country's installed capacity)

Quantification and adaptation

⇒ Model-based, reference vs risk-based scenarios

⇒ Decline in HPPs generation to be compensated by up to 4% of country's installed capacity by 2040



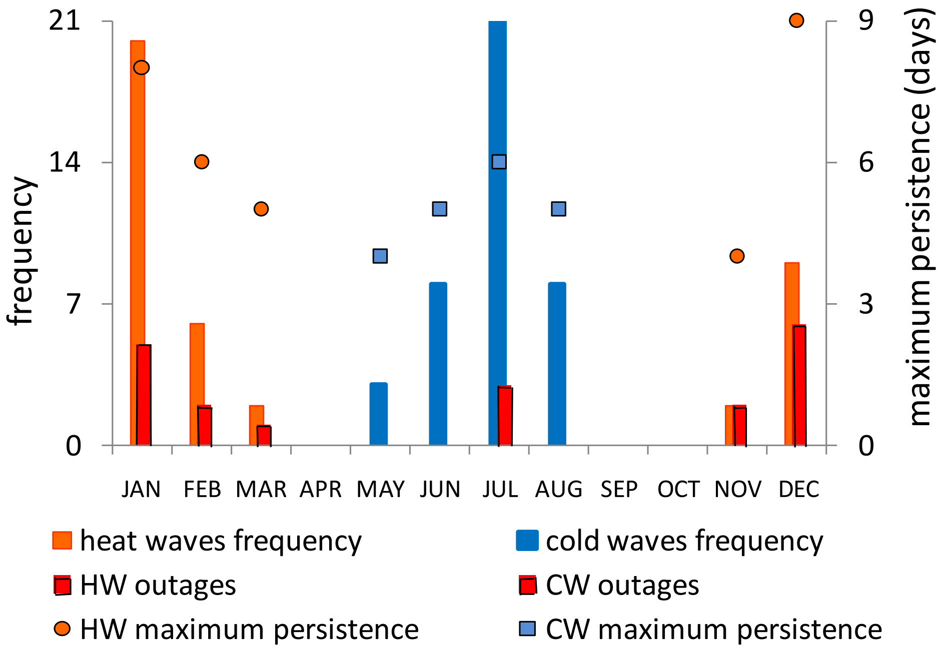
- Vulnerability analysis indicates no threat to NPPs

⇒ Methodology for *siting* of nuclear power plants, incl. possible flooding (eg. 23 m above the level of Parama river for Atucha I and II) and water availability for cooling

Source: Derived from CNEA

CRP Case study: Argentina

- Desinventar database: key vulnerability in the electricity sector to EW events
- Special focus: heat waves / cold waves and power outages



Monthly frequency of extreme temperature events and power outages in the Buenos Aires metropolitan area (1971-2013)

Vulnerability

⇒ increased vulnerability of the electricity system, in particular its distribution component;

⇒ Distribution system more vulnerable to heat waves than cold waves, more vulnerable in megacity than smaller cities suffering equivalent heat waves conditions

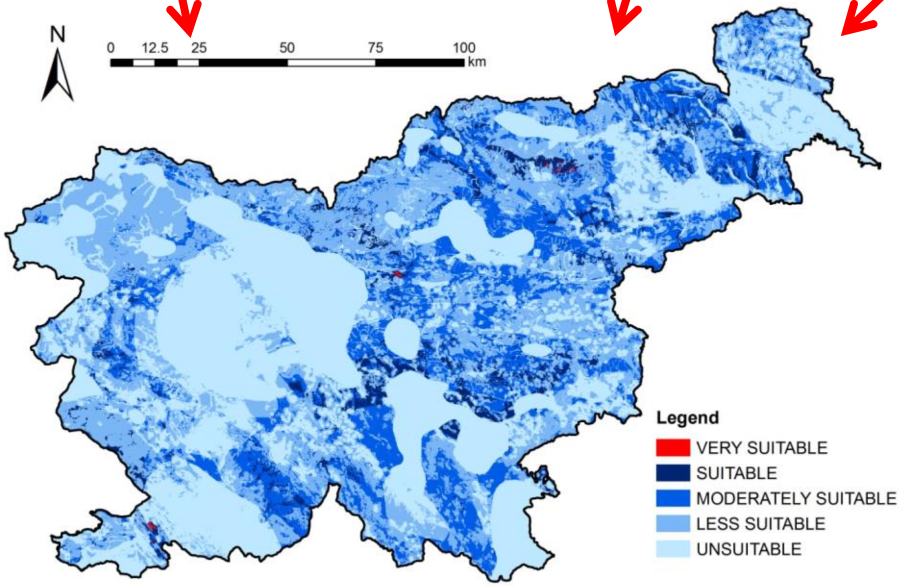
Source: Derived from CNEA

CRP Case study: Slovenia

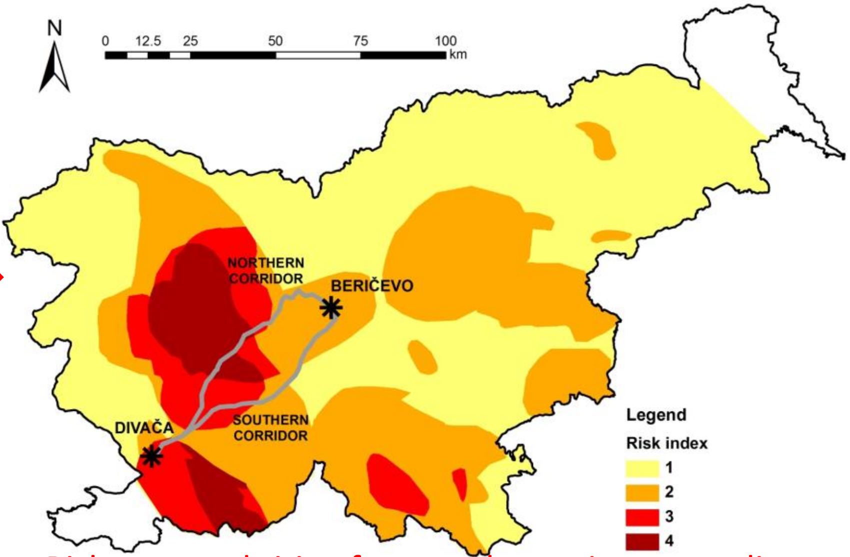
- GIS supported vulnerability evaluation
- Risks to power grids due to ice storms
  - Siting of transmission line
  - Siting of windfarms

Spatial Attractiveness

Environmental Vulnerability



Risk-assessed spatial suitability for windfarms



Risk-assessed siting for two alternative power lines

Windfarms

⇒ Very suitable area: 31 km^2

⇒ Potential capacity: 930 MW

⇒ Potential annual energy production: 1.68 TWh

Source: Derived from "Jožef Stefan" Institute

Towards more resilient energy sector

- Different analytical frameworks – identify, assess, adapt
- Cumulative investment over 2014-2040: US $25 trillion in oil and gas supply; US $20 trillion in power supply
- Sectors with large inertia – long lived assets
- Design and build with CC in mind: climate-safe

Source: Derived from IEA

Examples of CC impacts on NPP

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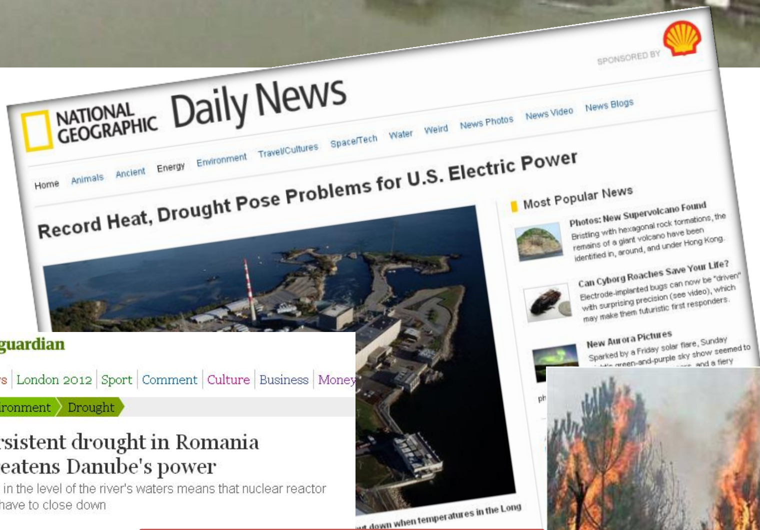
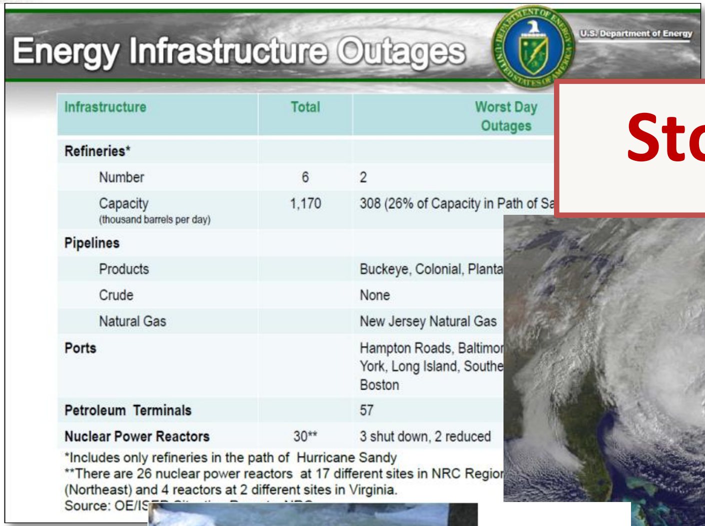
Floods



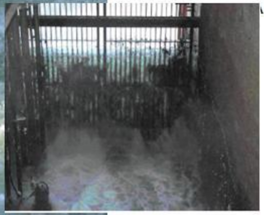
Drought / heat wave



Infrastructure	Total	Worst Day Outages
Refineries*		
Number	6	2
Capacity (thousand barrels per day)	1,170	308 (26% of Capacity in Path of Sa
Pipelines		
Products		Buckeye, Colonial, Planta
Crude		None
Natural Gas		New Jersey Natural Gas
Ports		Hampton Roads, Baltimor York, Long Island, Southe Boston
Petroleum Terminals		57
Nuclear Power Reactors	30**	3 shut down, 2 reduced

*Includes only refineries in the path of Hurricane Sandy
**There are 26 nuclear power reactors at 17 different sites in NRC Regior (Northeast) and 4 reactors at 2 different sites in Virginia.
Source: OE/IS

Storms



Frazil ice

Forest fires

Ice storms

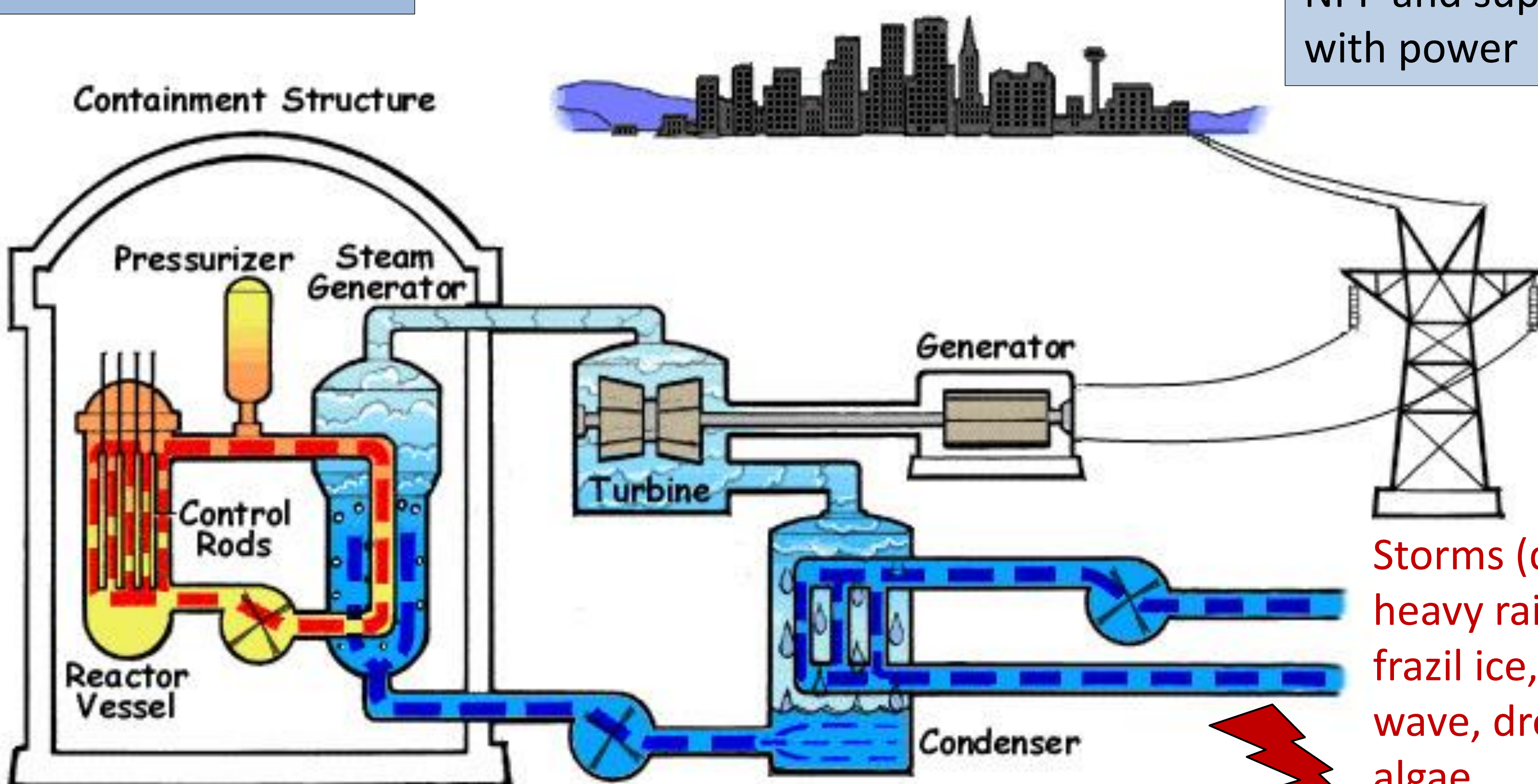
How can CC events affect a NPP?

<u>Containment:</u> ultimate barrier between reactor and environment

Floods, heat wave

Storms (wind, debris), ice storms, forest fires, heat wave

<u>Grid</u>: take power from NPP and supply NPP with power



Storms (debris), heavy rain, floods, frazil ice, heat wave, drought, algae, …

<u>Auxiliary blds:</u> emergency power gen. & other equip.

Floods, heat wave, snow storms

<u>Cooling water</u>: cool condenser & remove decay heat

Cooling for thermo-electric power plants

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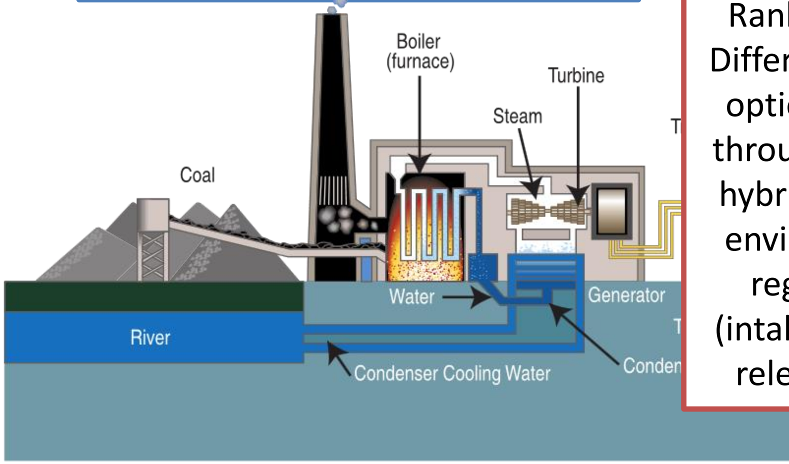
NORMAL OPERATION

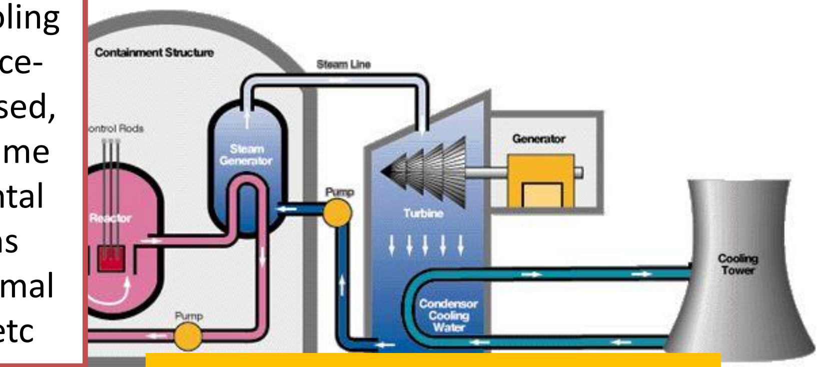
THERMAL EFFICIENCY

Fossil



Same issues:
Rankine cycle, Different cooling options (once-through, closed, hybrid…), same environmental regulations (intake, thermal releases), etc

Nuclear

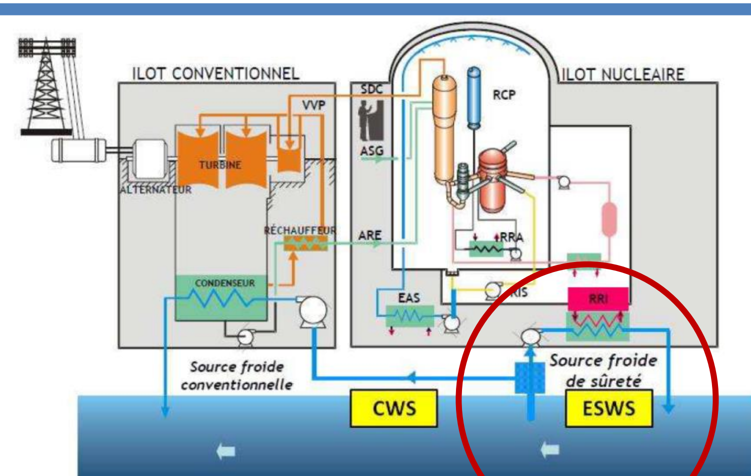


Circulating Water System (CWS)

ACCIDENTAL CONDITIONS

SAFETY

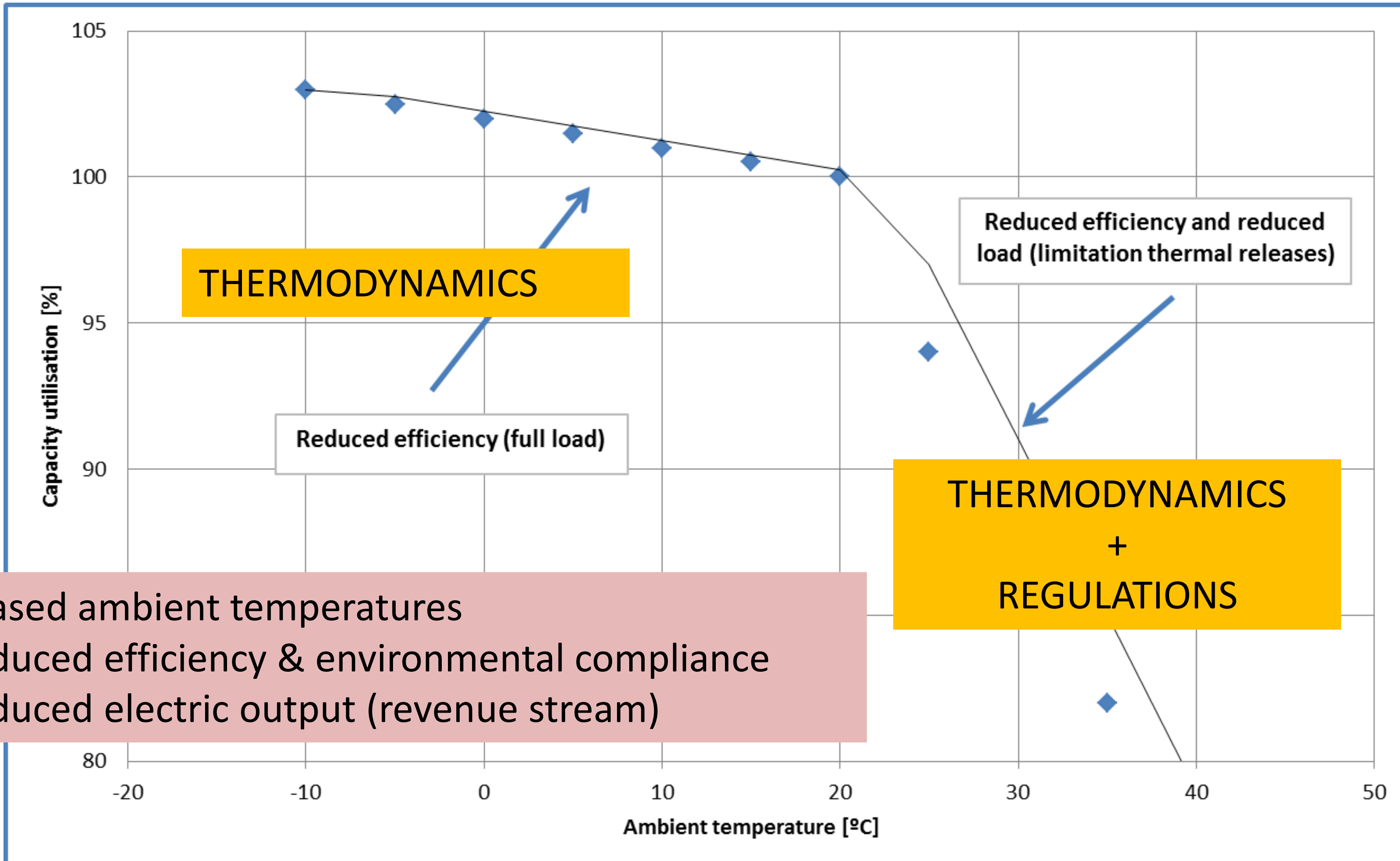
Shut down → no fuel → no residual heat



Essential Service Water System (ESWS) to remove residual (decay) heat: “Ultimate Heat Sink”

Cooling for thermo-electric power plants

Thermal Efficiency decreases with increasing cooling temperature
(thermodynamics AND environmental regulations)



Increased ambient temperatures
→ reduced efficiency & environmental compliance
→ reduced electric output (revenue stream)

What data do we have?

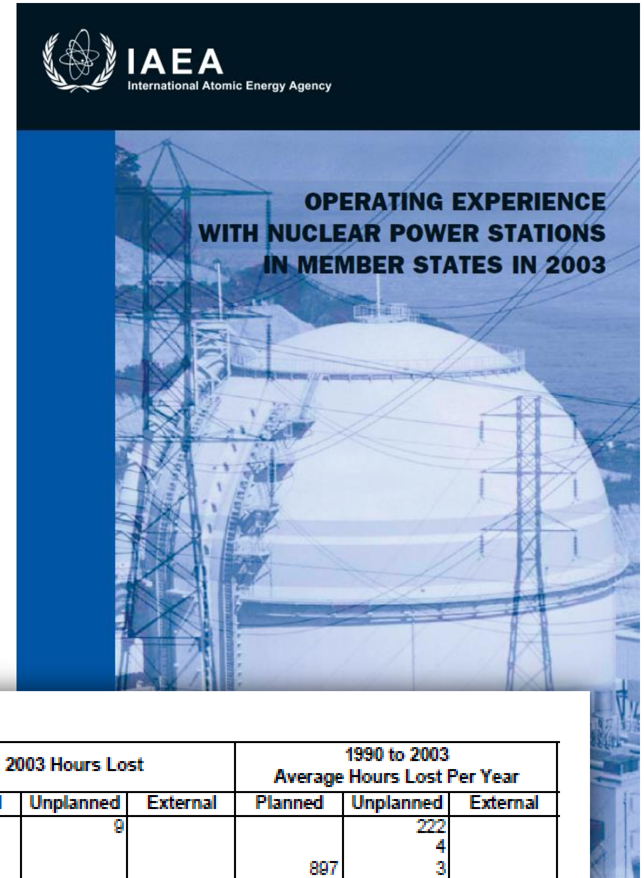
- IAEA Outage data (loss of kWh production) according to several classifications

2003 Operating Experience

FR-61 GOLFECH-1

6. 2003 Outages

Date	Hours	GW(e).h	Type	Code	Description
25 Jan	21.0	27.0	UF3	Z	VARIOUS, UNIT OPERATIONAL PROBLEMS (SOME NOT EXPLAINED)
04 Mar	1671.0	21.0	XP	K	OPERATION WITH POWER LIMITER BELOW MAXIMUM AVAILABLE POWER
11 May	8.0	2.0	PP	E	PERIODIC TESTING WITH LOAD REDUCTION OR SHUTDOWN
01 Jun	631.0	33.0	XP	K	OPERATION WITH POWER LIMITER BELOW MAXIMUM AVAILABLE POWER
02 Jun	31.0	19.0	XP	S	LOAD LIMITATION OR SHUTDOWN CAUSED BY INDUSTRIAL ACTION
13 Jun	16.0	7.0	UP3	A33	AIR COOLANT
22 Jun	9.0	12.0	UF3	A33	CIRCULATING PUMP
23 Jun	14.0	9.0	UP3	A16	STEAM GENERATOR INCLUDING SG BLOWDOWNS
01 Jul	697.0	27.0	XP	K	OPERATION WITH POWER LIMITER BELOW MAXIMUM AVAILABLE POWER
04 Jul	39.0	25.0	UP3	A32	FEEDWATER PUMP (EXCLUDING TURBINE-DRIVEN FEEDWATER PUMP)
01 Aug	335.0	20.0	XP	K	OPERATION WITH POWER LIMITER BELOW MAXIMUM AVAILABLE POWER
15 Aug	406.0	532.0	XF	N	COMPLIANCE WITH REGULATIONS CONCERNING RIVER TEMPERATURES
01 Sep	216.0	3.0	UP3	K	VARIOUS, UNIT OPERATIONAL PROBLEMS (SOME NOT EXPLAINED)
10 Sep	178.0	91.0	XP	K	LOAD VARIATION
16 Sep	81.0	4.0	XP	K	OPERATION WITH POWER LIMITER BELOW MAXIMUM AVAILABLE POWER
01 Oct	258.0	59.0	XP	K	FREQUENCY CONTROL, OPERA
02 Oct	167.0	5.0	XP	K	OPERATION WITH POWER LIMIT
01 Nov	476.0	20.0	XP	K	FREQUENCY CONTROL, OPERA
02 Nov	25.0	3.0	XP	K	REMOTE LOAD DISPATCH CONT
03 Nov	176.0	2.0	XP	K	OPERATION WITH POWER LIMIT
04 Dec	672.0	49.0	XP	S	LOAD LIMITATION DURING STR



7. Full Outages, Analysis by Cause

Outage Cause	2003 Hours Lost			1990 to 2003 Average Hours Lost Per Year		
	Planned	Unplanned	External	Planned	Unplanned	External
A. Plant equipment failure		9			222	
B. Refuelling without a maintenance					4	
C. Inspection, maintenance or repair combined with refuelling				897	3	
D. Inspection, maintenance or repair without refuelling				81		
E. Testing of plant systems or components				85		
H. Nuclear regulatory requirements					3	
K. Load-following (frequency control, reserve shutdown due to reduced energy demand)					13	
N. Environmental conditions (flood, storm, lightning, lack of cooling water due to dry weather, cooling water temperature limits etc.)			406			
Z. Others		21				
Subtotal	0	30	406	1063	245	0
Total	436			1308		

What data do we have?

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Outages per cause from 2004 to 2011			
Cause	Duration (1000 h)	Energy Loss (TWh)	No. of events
A	2 728	648	12 039
B	299	149	236
C	3 391	2 807	2 216
D	600	307	1 336
E	140	28	6 238
F	213	134	54
G	496	376	80
H	284	65	483
J	642	58	1 327
K	2 007	165	4 873
L	47	14	608
M	38	37	35
N	2 776	112	3 215
P	6	5	23
R	438	47	642
S	874	78	836
T	125	1	88
U	0.07	0.03	1
Z	561	26	746
Total	15 665	5 054	35 076

IAEA PRIS database

Awareness of issues but limited economic impact so far

Outages caused by environmental conditions

0	Warm cooling water
1	Cold cooling water
2	Flood
3	Low water level
4	Lightning / thunderstorm
5	Storms (typhoon, hurricane)
6	Other weather-related
7	Non-W env.: pollution
8	Unspec. env. restriction
9	Earthquake / tsunami
10	Seasonal variation CWT
11	Excluded: not environmental (market, techincal, cleaning)

17.7% duration
2.2% Energy Loss
9.2% Events

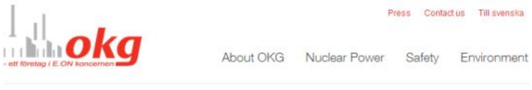
What data do we have?

- IAEA/NEA incident database, data from national reports, nuclear regulators and operators. Examples of shut downs due to external events:
  - Loss of “ultimate heat sink”, Cruas NPP, France, December 2009 (due to blockage of ESWS intake by massive quantity of algae)
  - CWS water intake blockage, Olkiluoto NPP, Finland, January 2008 (due to frazil ice)
  - CWS water intake blockage, Osarshamn NPP, Sweden, September 2013 (due to jelly fish)
  - Loss of off-site power, Dungeness B NPP, UK, October 2013 (caused by debris landing on power lines during storm)
- Other data provided in the course of the NEA study in the form of “**case studies**”
- Data about incidents themselves, but often information about measures required by the regulators to reduce the risks of similar events.

Olkiluoto NPP

Reactor trip at Olkiluoto 2 as a result of the freezing of coolant

Seawater cooled rapidly in front of the Olkiluoto nuclear power plant on the morning of Saturday 5 January 2008. The frazil ice formed as a result of this cooling blocked the circulating water screening filters of Olkiluoto 2 and weakened the flow of the seawater used as coolant in the plant. As a result, a turbine trip occurred at the plant unit, leading to a reactor trip. In connection with the event, a steam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Jellyfish cause stop of production at unit Oskarshamn 3

Published 2013-09-30 13:27

At noon on Sunday 29 September, the production at unit Oskarshamn 3 (O3) was manually shut down due to a large amount of jellyfish present at the cooling water intake.

The operations management at unit O3 chose to disconnect the facility from the grid at noon on Sunday due to a large amount of jellyfish present at the cooling water intake. This decision is a preventive safety measure in order for the unit to not be automatically shut down due to too low cooling in the condenser.

The function of the cooling water in the condenser is to cool down the steam so that it is reformed in to water again, and subsequently brought in to the reactor vessel. This cooling water has no connection to the cooling of the reactor vessel.

Adaptation measures

Adaptation Measures in Finnish NPPs

- **Olkiluoto NPP:**
  - Measures to prevent blockage (by snow) of air intakes of heating, ventilation and emergency diesel generators
  - OL3: heating of air intakes
  - Pumping "warm water" upstream of cooling water intake to prevent frazil ice formation

- **Loviisa NPP:**
  - Construction of air cooling system (tower) to supplement sea cooling in case of frazil ice or other pbs with sea water
  - Heating water intake grids to prevent frazil or pumping warm water upstream
  - Study on building deep water intake in case of high sea temperatures (possibly economical in the future)

Adaptation measures

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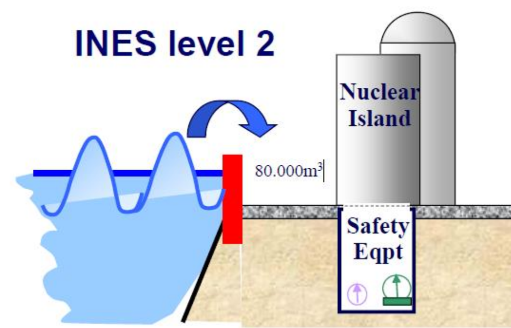
Adaptation Measures in French NPPs

- **Le Blayais flooding (Dec. 1999)**
  - High tide + storm surge + waves generated by high wind in the estuary (not linked to CC) → exceeded the worst-case "design scenario"
  - Water went over the dikes – flooding of NPP site and in units 1 & 2
  - INES level 2



- **Review of flood risks / adaptation**
  - Re-assessment of flood risks for all 19 NPPs
  - Improvements where necessary (elevated dikes, water tight doors, plugging, etc) & specific flood procedures
  - Upgraded protection of most NPP against floods – for a cost of 110 M€

EDF presentation, RIC 2010, External flood and extreme precipitation hazard analysis

The cost of 'inaction'

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- Direct impact:
  - Loss of production due to partial/full outage because of:
    - compliance to environmental regulations (e.g. thermal releases) or safety regulations (max. temp. cooling water for safety-related cooling systems) or
    - Event affecting operation of NPP (e.g. the cooling system) or
    - Event affecting the transmission grid.
  - Loss of efficiency due to higher cooling water temperature (data not publically available)
  - Cost of repairs, refurbishment, safety upgrades
- Indirect impact:
  - Purchase by utility of power on "spot market" to compensate for loss of production
  - Compensation of customers (energy-intensive industry) required to reduce their electricity consumption (load management/shedding)
- Who pays what? Insurers, operators, tax payers?

Dealing with CC in the nuclear sector

- Guidelines (e.g. siting), safety standards, safety assessments and regulations
- Design (e.g. taking into account CC risks)
- Technology (e.g. cooling technologies, reactor design, on-site water production)
- Planning and plant management (e.g. based on demand forecast, outage planning)
- Demand-side management

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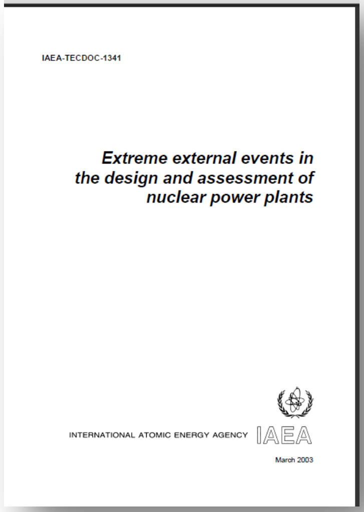
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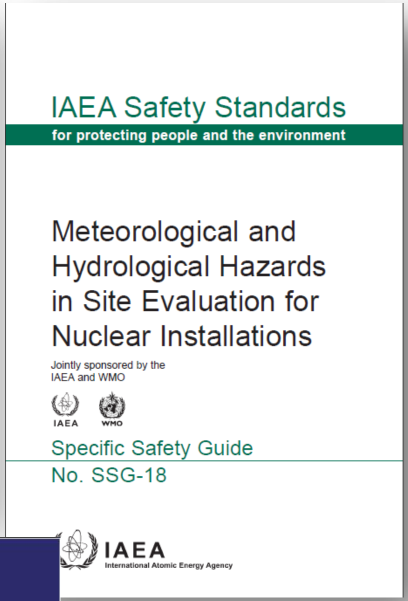
Extreme external events in the design and assessment of nuclear power plants

INTERNATIONAL ATOMIC ENERGY AGENCY IAEA

March 2003


IAEA Safety Standards

for protecting people and the environment

Meteorological and Hydrological Hazards in Site Evaluation for Nuclear Installations

Jointly sponsored by the IAEA and WMO

IAEA WMO

Specific Safety Guide

No. SSG-18

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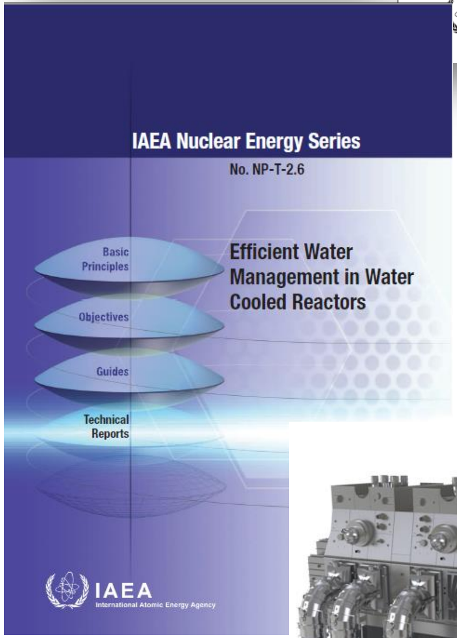
IAEA Nuclear Energy Series

No. NP-T-2.6

Basic Principles

Objectives

Guides

Technical Reports

Efficient Water Management in Water Cooled Reactors

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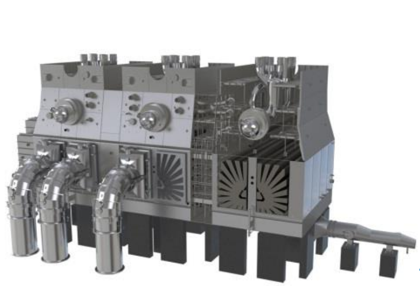
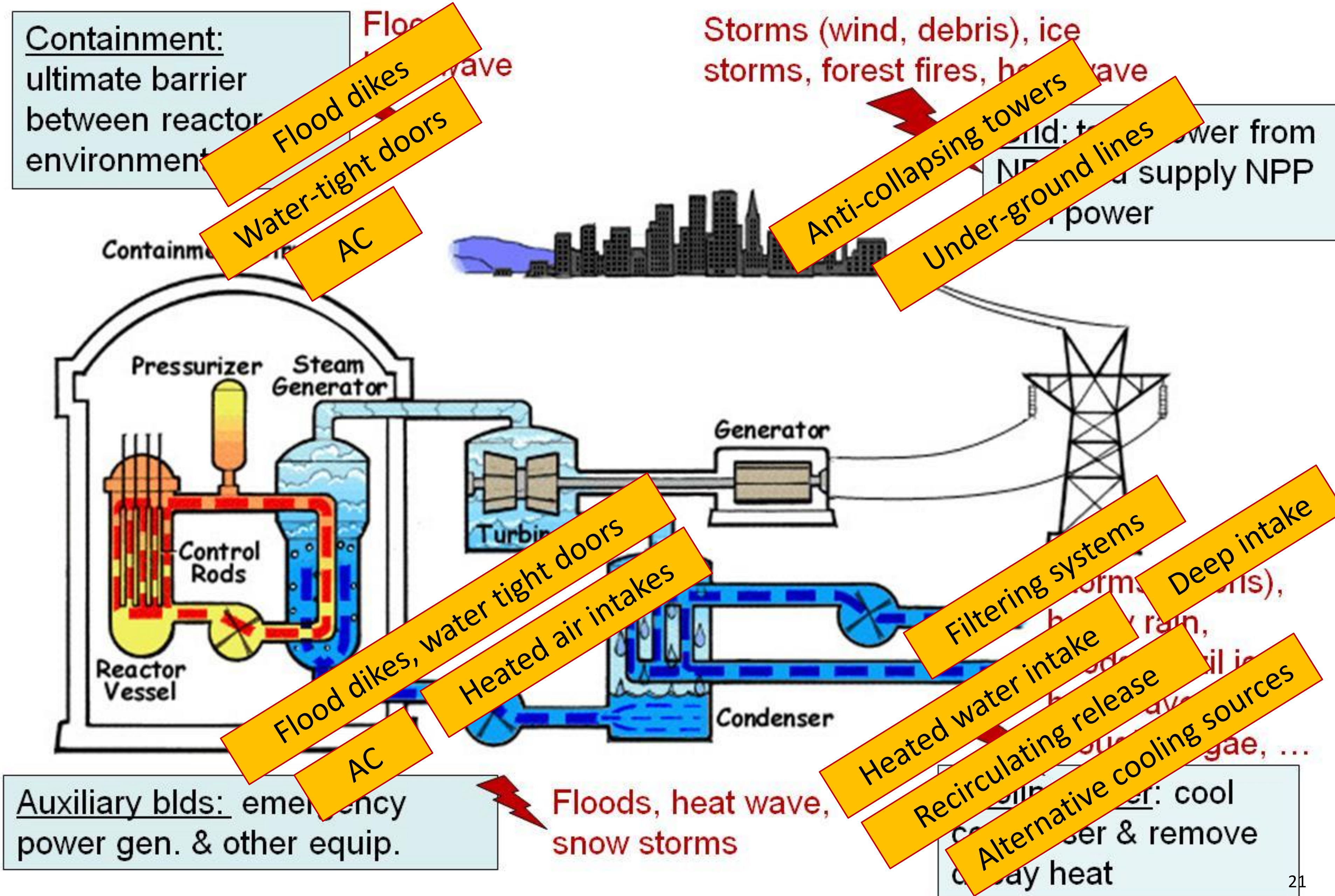


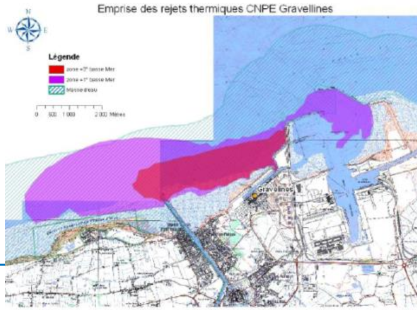
Technical solutions



R&D needs

- <u>Technology:</u> (objectives: reduced usage of water / reduced impact / reduced costs)
  - ➢ Cooling technologies:
    - Closed cooling systems, hybrid systems
    - “low” profile cooling towers (public acceptance)
    - Dry cooling (e.g. Bilibino NPP, Russia)
    - More efficient Heat Exchanger equipment (e.g. Condensers)
  - ➢ Modelling of cooling water intakes & thermal releases to reduce environmental impact and/or improve efficiency (*)
  - ➢ non-traditional water resources (e.g. Treated waste water) (e.g. Palo Verde, AZ, USA)
  - ➢ On-site production of “fresh” water (desalination)
  - ➢ Innovative reactor designs (e.g. Gen IV, higher operating temperatures/efficiency) - Advanced power conversion technologies (e.g. SCO2)

Palo Verde NPP, largest NPP in the United States, uses treated waste water from city of Phoenix and other municipalities.



R&D needs

- <u>Weather forecast:</u> (objectives: improved management of supply [e.g. Outages] and demand)

- Planning based on better assessment of demand.
  - "air temperature" is most important parameter driving electricity demand. (e.g. In France, in winter, -1ºC ~ 2300 MW electricity production)
  - predicting consumption with 1 to 2 weeks lead-time can help optimise selection of generating units to meet demand.
- Planning outages:
  - planning refuelling and maintenance outages during peak heat periods (provided outages can be balanced by increased production at other sites or imports) for most vulnerable units (located on rivers)
  - After 2003 heat wave, EDF reviewed its maintenance planning to ensure operation of all coastal units during summer

- R&D to improve forecasting tools:
  - to select, size and engineer future plants, test robustness against CC / extreme weather events.
  - Multi-scale approaches to combine long-term forecasts (several decades, time scale of investment / construction / operation) with short term projections (for operational purposes, fleet management)

Conclusions

- **New plants:** (typically 60 year lifetime → operation until ~2080)
  - ➢ Design, siting – take into account CC risks. (max. sea level rise, max. temp., max. wind speed, etc...).
- **Existing plants:**
  - ➢ Siting and safety case take into account (known) extreme weather events
  - ➢ Safety requirements are always a driver for change (often, safety upgrades improve CC resilience too). For non-safety issues: (e.g. thermal efficiency, outages due to environmental reasons), "economic decision"

INACTION

- *cost of adaptation vs. electricity market 'economics' (wholesale price, overcapacity)*
- *adaptation can lead to reduced power output (e.g. closed cycle vs. direct cooling)*
- *single plant operator*
- *remaining lifetime (~10y)*
- *"low" number of events*

ADAPTATION

- *safety requirements*
- *fleet operator*
- *remaining lifetime (~20-30y)*
- *"high" number of events*
- *security of energy supply*

Need to make the economic case for resilience

Conclusions

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- Importance of addressing (generation + grid + consumers) together to design resilient energy systems

- (Short term) economics not enough to drive changes (viewed as **costs**):
  - Role of governments to put in place **investment** framework for long term
  - Role of regulations to drive technological changes.

- In terms of R&D needs / activities with respect to nuclear power & CC:

  - Cooling & other technologies *to reduce water dependence*
  - Forecasting methods *to improve plant/fleet management & balance supply & demand*
  - Safety assessment methods *to address future CC events in design & safety cases*
  - Economic assessment methodology *to make a better case for adaptation.*

- **Nuclear power technology is adapting to CC to make it safer & more resilient against Climate Change: a robust low C generating solution for the future!**