Enhancing Climate Resilience at Leibstadt NPP: State-of-the-Art Meteorological Hazard Assessment and Adaptation Measures

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Albena Stoyanova
Department of Nuclear Safety
Leibstadt Nuclear Power Plant

Kernkraftwerk Leibstadt AG
CH-5325 Leibstadt | Telefon +41(0)56 267 71 11 | www.kkl.ch

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Enhancing Climate Resilience at Leibstadt NPP

Outline

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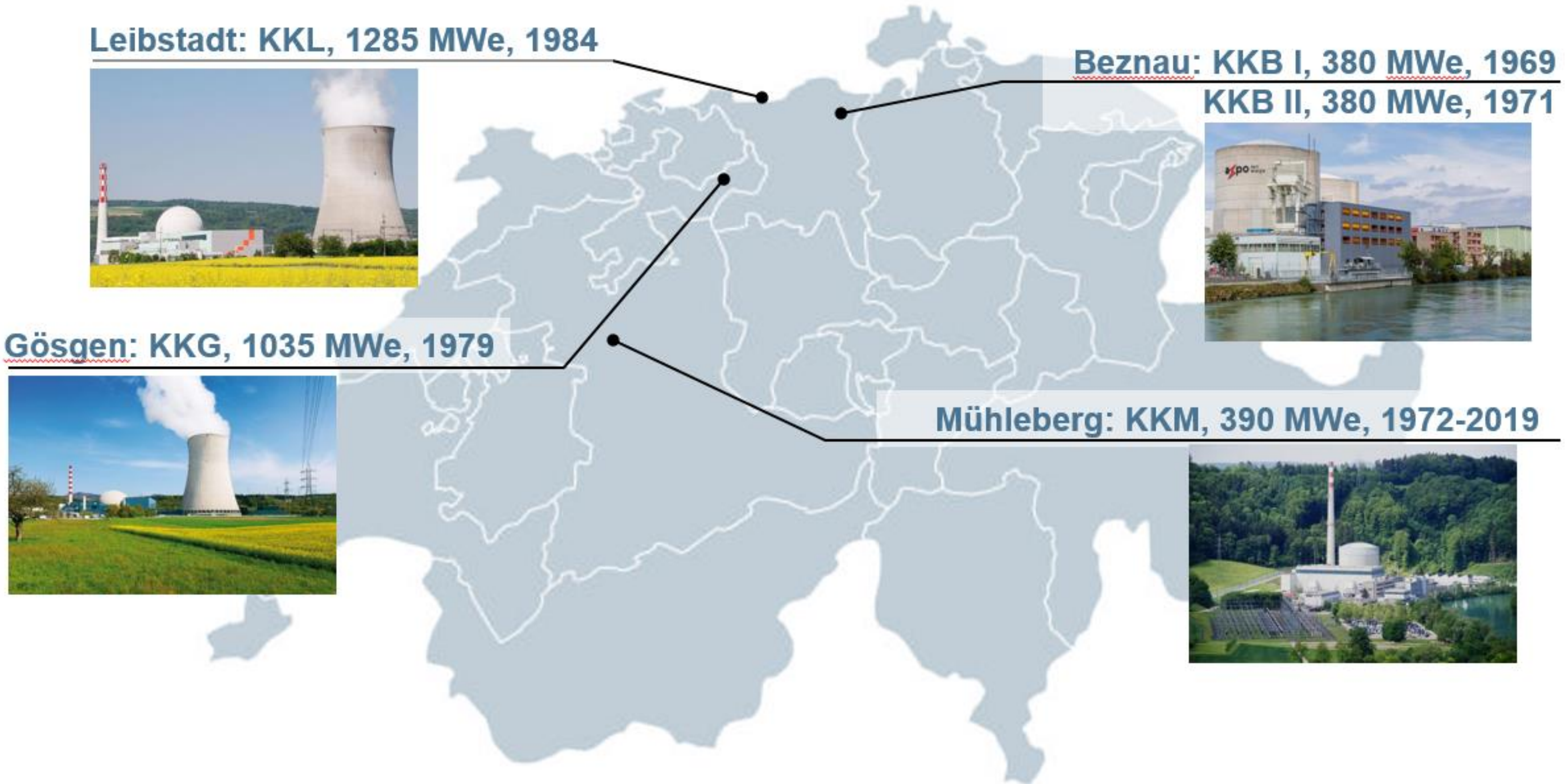
NPPs in Switzerland



- ***swissnuclear*** coordinates the overall process, including data acquisition, plausibility checks and communication
- Each plant conducts meteorological hazard analyses using a standardized approach

Enhansed Regulatory Requirements

- Extreme Weather Hazard Analyses for NPPs Beznau, Gösgen and Leibstadt; including climate change considerations
- Strengthened hazard assumptions for demonstrating safety for 1 000- and 10 000-year event
- Pre-defined list of Extreme weather conditions:
  - Quantitative Analysis:
    - ✓ Air and Riverine temperature
    - ✓ Precipitation
    - ✓ Wind Gusts and Tornadoes
    - ✓ Snowfall and Snowload
  - Qualitative Analysis:
    - ✓ Hail
    - ✓ Ice Rain
    - ✓ Forest Fire
    - ✓ Drought
    - ✓ Combined extreme summer conditions
    - ✓ Combined extreme winter conditions
- Swiss-specific climate projections CH2022
- Additional considerations of phenomena not captured in the observational records (e.g., effects of volcano eruptions, hystorical data)
- Prescribed methodology for quantitative analyses: Extreme Value Statistics (except Tornadoes)

Neue Gefährdungsannahmen

Gefährdung	KKB	KKG	KKL	KKM
Extremer Wind	Tornado wird zugrunde gelegt			
Tornado	63 m/s	63 m/s	63 m/s	58 m/s
Hohe Lufttemperatur**	+ 43,1 °C	+ 43,7 °C	+ 43,7 °C	+ 42,2 °C
Tiefe Lufttemperatur	– 30,0 °C	– 30,0 °C	– 30,0 °C	– 30,0 °C
Hohe Flusswassertempera-tur	+ 30,0 °C	+ 30,0 °C	+ 30,0 °C	+ 30,0 °C
Tiefe Flusswassertempera-tur	Auftreten von Eisbrei			
Starkregen**(2 h Maximal-Niederschlag*)	145 mm oder	150 mm oder	150 mm oder	135 mm oder
	maximal mögliche Wasseransammlung auf den Gebäudedächern			
Schneelast	2,7 kN/m²	3,1 kN/m²	2,6 kN/m²	3,3 kN/m²
Hagel	Hagelkorn mit 15 cm Durchmesser; maximale Fallge-schwindigkeit 55,0 m/s			

KKL Site-specific Extreme Weather Analysis

Station Pre-Selection

- Measurement data mainly provided by national meteorological service

- First rough pre-selection of sites through data order

- Radius around site (50 km; similar climatic conditions)

- Similar altitude (<700m)

- Station Exposition (depending on hazard)

- Sufficient data quality and quantity (>30 years, strict treatment of missing values)

Data Preparation & Exploration (EDA)

- Choose block length, take maxima (*bias-variance-tradeoff* → monthly maxima, except snow)

- Scatterplots → final station selection

- Plot the data → trends?

- Exploratory Modeling to decide how to model seasonality & which months to exclude, ensuring a constant shape parameter

Statistical Modeling

- Decision on trend in location parameter automatically (Mann-Kendall-Tests)

- Parameter Estimation of time-varying GEV distributions (Maximum Likelihood)

- Goodness-of-Fit: Likelihood-Ratio-Tests, graphical comparisons of observations vs model-simulated data

- Derivation of *annual* return levels for the last year in the data (GEV quantile function / root-finding algorithm)

- Calculation of regional mean hazard curves (modification of inverse distance weighting)

Uncertainty Analysis

- Parametric Bootstrap (1000 samples)

→ Frequentist *Confidence* intervals (≠ Bayesian *credible* intervals)

→ quantify *estimation uncertainty*

- All analytical steps implemented using a functional programming language R
- Unified process applied to all hazards, enabling seamless updates and future enhancements

Objective: deliver high-quality results using state-of-the-art methods and software

KKL Methodology

Quantitative to evaluate hazards are assesst based on the following steps:

- Data pre-processing
- Exploratory Data Analysis
  - Trend and deasonality assessment
  - Spatial dependence evaluation
- Extreme Value Analysis
  - Block Maxima Method
  - Goodness-of-Fit testing
  - Uncertainty Analysis
- Hazard Curves Development
- Return Levels Estimation
- Plausibility checks
- Assessment of climate change impacts

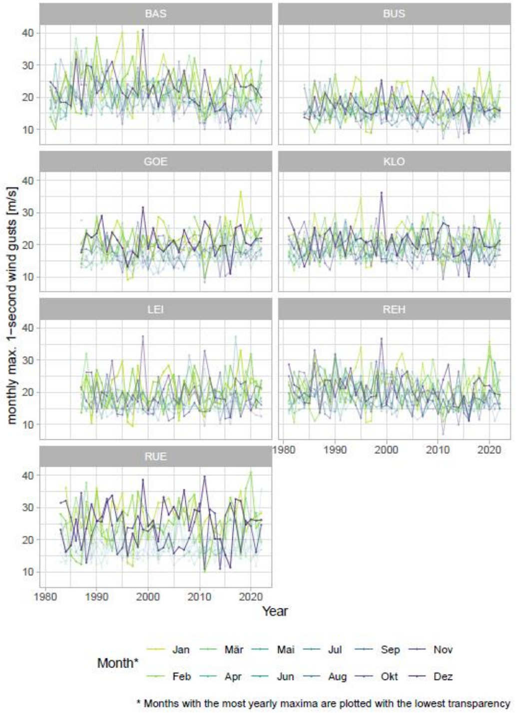


Figure 4-1: Monthly maxima of 1-sec wind gusts

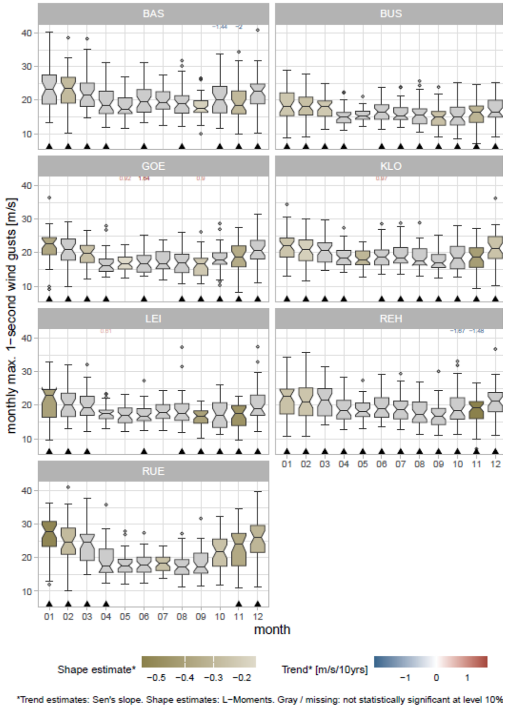


Figure 4-2: Seasonality check for monthly maxima of 1-sec wind gusts

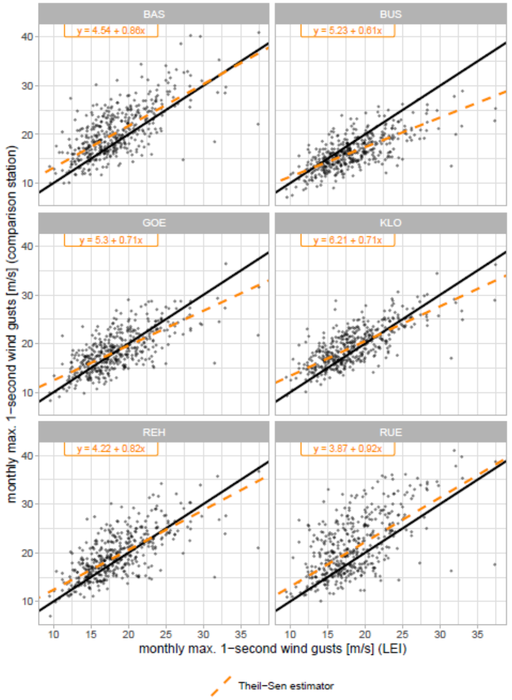


Figure 4-3: Spatial dependence for monthly maxima of 1-sec wind gusts

Table 4-1: Estimated GEV distribution parameters for 1-sec wind gusts

station	model	$\hat{\mu}_0$	$\hat{\mu}_1$	$\hat{\mu}_2$	$\hat{\mu}_3$	$\hat{\sigma}_0$	$\hat{\sigma}_1$	$\hat{\sigma}_2$	$\hat{\xi}$
BAS	$\mathcal{M}_{TS,S}$	$19.39_{0.40}$	$-0.46_{0.15}$	$0.84_{0.28}$	$0.99_{0.29}$	$4.34_{0.15}$	$0.46_{0.20}$	$0.89_{0.20}$	$-0.11_{0.03}$
LEI	$\mathcal{M}_{S,S}$	$16.54_{0.19}$	$0.50_{0.24}$	$0.70_{0.25}$		$3.43_{0.13}$	$-0.45_{0.19}$	$0.93_{0.16}$	$-0.04_{0.03}$
REH	$\mathcal{M}_{TS,S}$	$18.50_{0.37}$	$-0.41_{0.14}$	$1.06_{0.25}$	$0.45_{0.26}$	$3.98_{0.14}$	$0.35_{0.18}$	$0.86_{0.18}$	$-0.12_{0.03}$
RUE	$\mathcal{M}_{S,S}$	$19.19_{0.26}$	$-0.23_{0.29}$	$3.24_{0.33}$		$4.78_{0.18}$	$-0.38_{0.20}$	$1.82_{0.22}$	$-0.18_{0.03}$

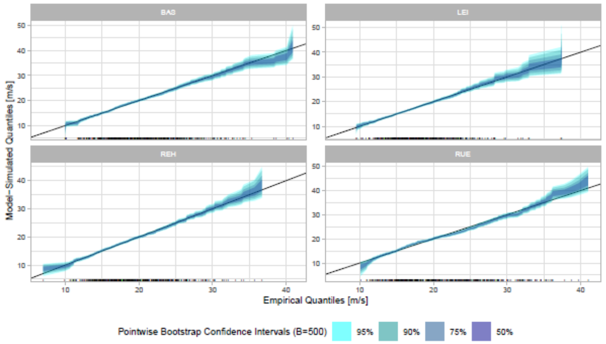


Figure 4-4: QQPlots of the estimated GEV models for wind

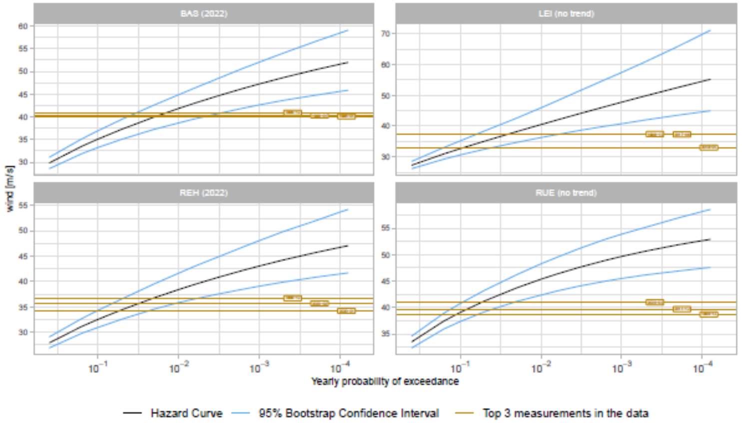


Figure 4-5: Hazard curves for wind

KKL Extreme Weather Analysis

- Compliance with regulatory requirements through methodological enhancements:
  - Advanced, mathematically robust analyses
  - Systematic and reproducible modelling approach
  - Comprehensive regional assessment of meteorological hazards
  - Plausible results, even for very low annual exceedance probabilities
- Consideration of current and appropriate climate data of assured quality;
- Historical climate data reviewed for plausibility (notably uncertain for extremes, except hydrology)
- Consideration of weather phenomena absent from data records;
- Use of Swiss climate projections – CH2022, Hydro CH2018 / 2021;
- Consideration of both past and future climate change
- External Flooding analysed separate and excluded for the KKL site

Basis for site-specific Probabilistic and Deterministic Safety Analyses

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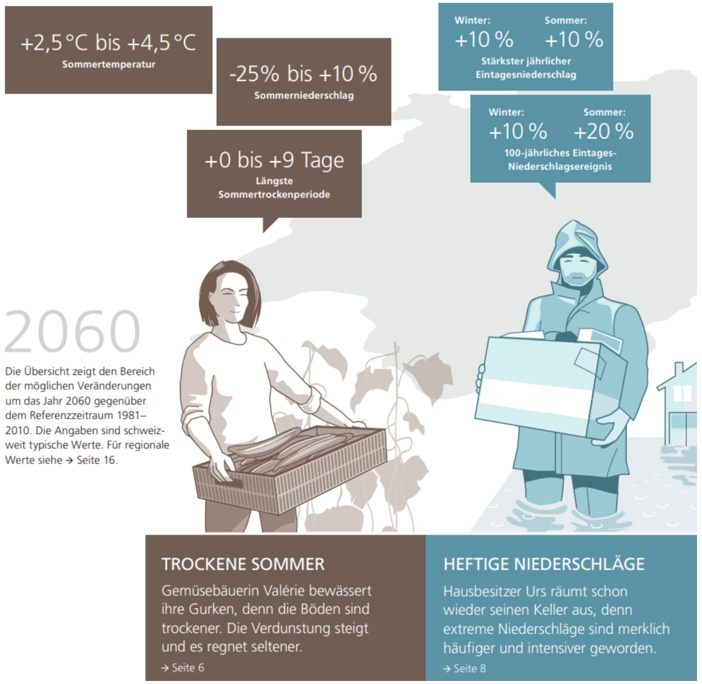
Future Climate Change: Scenarios considered in KKL Analysis

- Conservative approach by comparison of:
  - Trends estimated by the KKL-specific models;
  - Projections of Climate Models in Switzerland: pessimistic emission scenario (RCP8.5 Scenario without Climate Protection);
- Future climate change considered up to next PSR (2032):

Both approaches are applied and the more conservative future trend is assumed and used in the estimation of return levels.

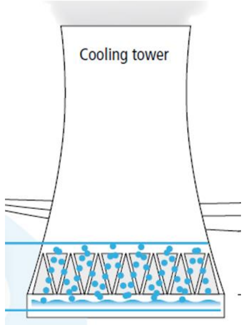
Conservatively, no future trends are assumed for hazards decreasing in magnitude: snow precipitations, low air and river water temperature.

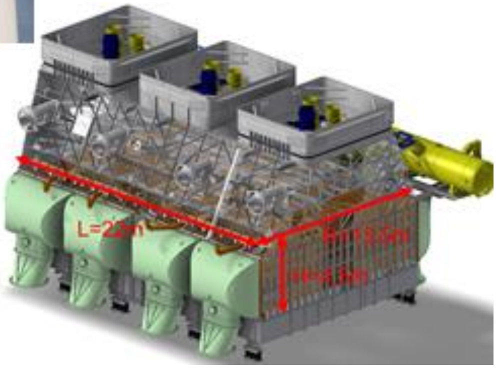


CH-2022 Climate scenarios in Switzerland

Operational Experience

- *Power losses:*
  - Average annual loss of approximately 4,000 MWh over the past 10 years (total ~40,000 MWh)
  - KKL produces about 10 TWh gross per year
- *Hot summer challenges:*
  - Reduced cooling tower efficiency and condenser vacuum during hot summers
  - Since main condenser replacement in 2021, power reductions are no longer required; vacuum loss on warm days significantly reduced (previously 20–200 MW)
  - 2008–2012: cooling tower internal modifications improved efficiency by 12–15 MW
- *River temperature restrictions:*
  - Administrative limit on cooling water temperature discharged to the Rhine
  - Rhine water temperatures have increased since plant commissioning in 1984
  - Future reconsideration of the administrative limit may be necessary
- *OPEX:*
  - No observed impact of climate change on component or system operability
  - No incidents of I&C system compromise due to high ambient temperatures





No SCRAMs or unavailability of SSC due to the climate change

Continuous Improvement

Plant modifications to enhance preparedness:

- 2008 – 2012: Cooling tower aerodynamics modification
- 2021: Replacement of main condenser
- 2016 – 2021: Replacement of air supply system chillers with new, more efficient units in:
  - ✓ Remote shutdown areas;
  - ✓ Main control room;
  - ✓ Operational building;
  - ✓ Active Workshop;
  - ✓ Turbine building.
- 2020-2033: Digitalisation of Safety I&C:
  - ✓ Backfitting with appropriatly qualified equipment;
  - ✓ Seismic and environmental qualification of Teleperm XS;
  - ✓ Temperature monitoring inside the cabinets.

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KKL cooling tower - aerodynamics

Flow tests / visualisation of the air flow

Before

After

Air flow tests before and after the completion of the profiles show the positive effect of rounded edges

Realization and Improvement

- **KKL-cooling tower**
  thermal power ≈ 2400 MWth.
- **2011 Inlet profile „top“:**
  average improvement
  TVC ≈ 0.54 K
  (temperature cooling water)
- **2009 basin profile „bottom“:**
  average improvement
  TVC ≈ 0.4 K
- **Performance improvement Pel.:**
  TVC $_{ges.}$ ≈ 1.0 K (better cooling)
  Pel. ≈ 4 - 5 MWel.

An easy and economic way to improve the performance of a power plant sustainable.
(Payback - Time < 1 year)

Patent declared (KKL / KKG / EPPG)
EP10014199.3 (European 02.11.2010)
PCT/EP2011/069205 (international 02.11.2011)
=> Patent-publication since April 2011

Empfangsbescheinigung

Hiermit wird bestätigt, dass Ihr im folgenden bezeichneter Antrag auf Bearbeitung einer internationalen Anmeldung nach dem Vertrag über die internationale Zusammenarbeit auf dem Gebiet des Patentwesens (PCT) bei uns eingegangen ist:

Eingangsnummer	1384086
PCT-Aktenzeichen	PCT/EP2011/069205
Titel	LUFTEINFÜHRUNGSSYSTEM UND VERFAHREN FÜR KÜHLTÜRME

FIG. 5

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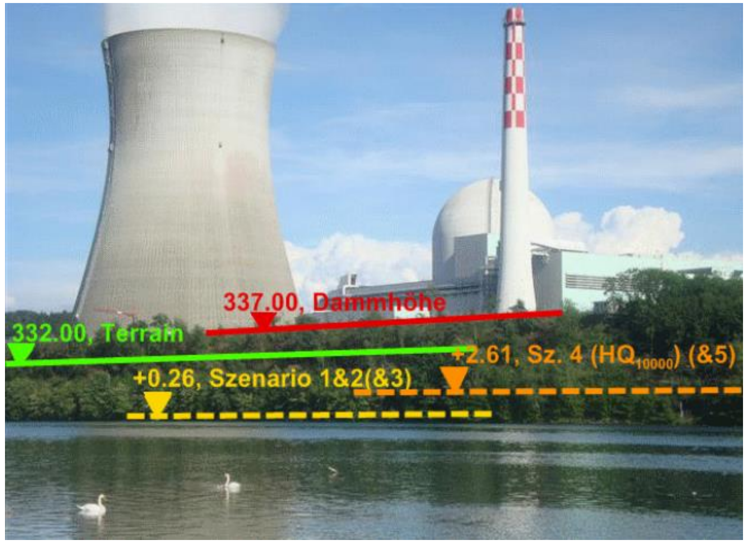
KKL Extreme Weather Preparedness

- Weather updates available in the Main Control Room;
- Rhine water level stabilized by RADAG and Dogern hydropower plants.
- Robust flood protection– «dry site» concept
  KKL site located 21m above the Rhein river water level;
- Redundant safety system cooling via groundwater wells
- Technical and administrative measures against extreme weather conditions in KKL procedures:
  - Commissioning of the hot water recirculation line of the Auxiliary cooling water system;
  - Test operation of the emergency cooling water towers at outside air temperatures below 3°C;
  - Operation of main cooling tower at outside air temperatures below 5°C;
  - Turbine hall ventilation to prevent icing of intake grill icing (especially in fog and below 0°C);
  - Ventilation of cold condensate tank building when room temperatures falls below 10°C;
  - Defrosting of DG air openings;
  - Countermeasures when Rhine water temperatures reach or exceed 25°C;
  - Forest fire risk mitigation measures;
  - Procedures for strong winds exceeding 100 km/h and tornadoes.



KKL Strategy: Remain resilient to face the climate change
Strengthen defense against external hazards

- **PLAN:**
  - Response to enhanced regulatory requirements
  - Identify critical SSCs and infrastructure
  - Access current and future vulnerabilities to natural hazards
  - Update site-specific extreme values
  - Integrate climate change considerations
  - Implement risk management
- **PREPARE:**
  - Conduct seasonal readiness activities: walkdowns, inspections, testing
  - Enhanced monitoring and preventive maintenance
  - Extennd plant life time
  - Train personnel
  - Improve safety culture and self-awareness
  - Maintain emergency preparednesss
  - Conduct crisis management drills
- **SITUATIONAL AWARENESS:**
  - Access real time information
  - Receive warnings on extreme events and seasonal forecasting from Swiss meteorological services
  - Observe future projection
  - Ensure functionality of communication networks, meteorological systems, environmental monitoring and information displays

- **ANTICIPATED AND MITIGATE**
  - Frequently inspect and monitor key equipment, systems, and vulnerable areas
  - Ensure equipment and system availability
  - Maintain internal and external communication
- **ABSORB AND RESPOND**
  - Monitor, communicate and coordinate
  - Implement Emergency Operating Procedures
  - Down power, shutdown the Reactor as needed
  - Operate in island mode if required
  - Ensure shutdown cooling
- **RECOVER**
  - Restore stable plant conditions
  - Maintain communication
  - Utilize black start capability
  - Deploy SAMG equipment
- **ADAPT**
  - Evaluate OPEX
  - Adapt operational procedures for all external hazards
  - Incorporate lessons learned into planning and preparation
  - Enhence organizational and technical capacity

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Thank you for your attention!

Albena.Stoyanova@kkl.ch

+41 56 267 8523

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