Lions International

Sapienza Università di Roma

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Le nuove tecnologie e le loro prospettive

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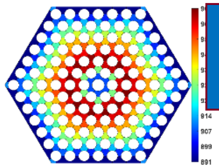
Intro

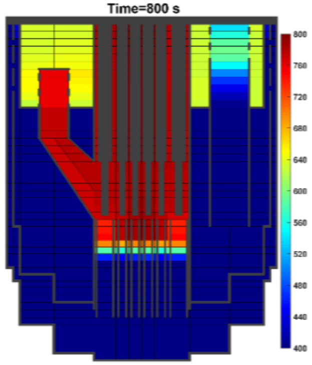
- Attività svolte da Sapienza nell'ambito ingegneria nucleare
- Reattori di tipo innovativo

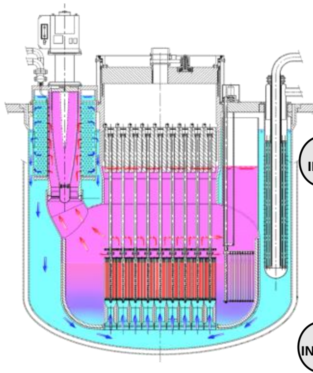
- Sicurezza Energetica
- Equità Energetica
- Sostenibilità Ambientale

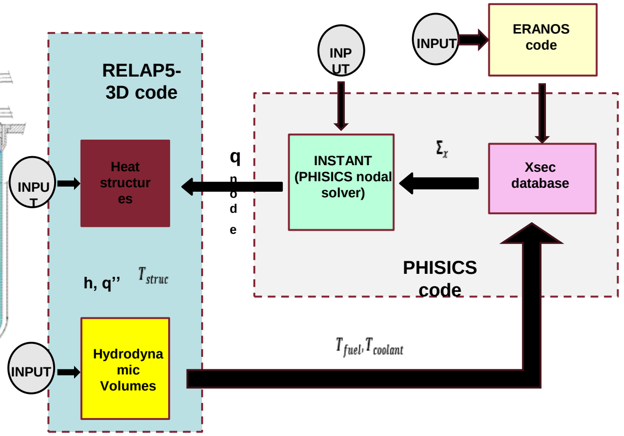
- Conclusioni

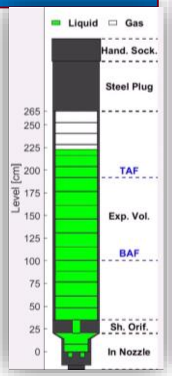
NERG – SMR and LFR TH analysis

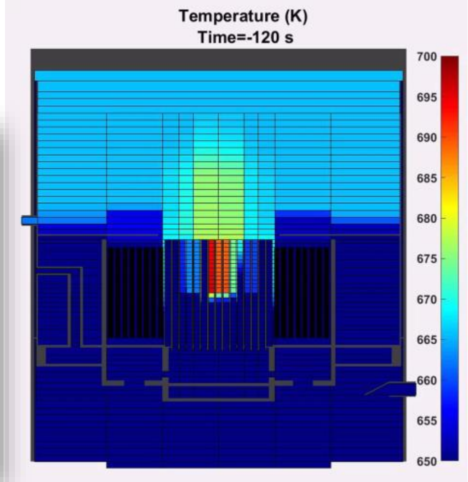


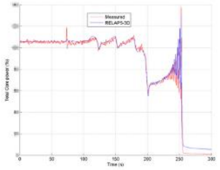


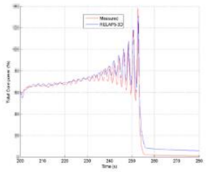


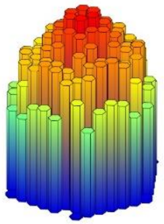










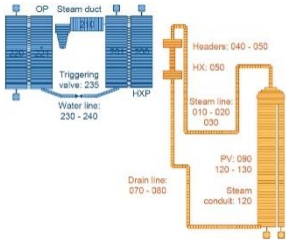


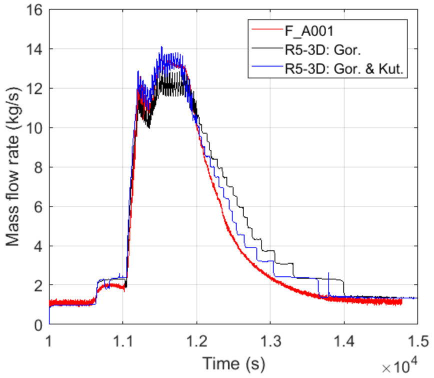
- Preliminary safety analysis with RELAP5 MARS-based iPWR
- Coupled thermo-hydraulic/neutron kinetics SFR and LFR analysis
- Thermal hydraulic analysis with RELAP5 and RELAP5-3D ALFRED reactor and IC
- RELAP5-3D validation for liquid metals
- Development of the EU-LOOP-SMR database
- Severe accident simulation with MELCOR for SMR and IVMR strategy analysis, Uncertainty Quantification (iPWR and BWR in progress)
- RELAP5 mod3.3 version development and validation with support experiments (helical coils, passive systems, MHD pressure drops, HTC correlations, other fluids)
- newcleo AS-200 pool thermal-hydraulic and NK-TH coupled simulations using ATHLET and R5

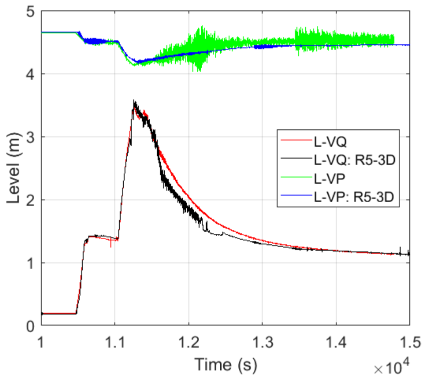
NERG – Recent international activity

NEA
NUCLEAR ENERGY AGENCY

- OECD/NEA/CSNI WGAMA State of art on reliability of thermal-hydraulic passive systems (SOAR-RPS) - PERSEO benchmark on passive systems
- WGAMA ISP-52 on Primary Coolant Loop Test Facility (PKL) experiment on Multiple SG U-tube rupture
- WPRS LWR-SMR benchmark (PRACTIC core and BWRx-300)

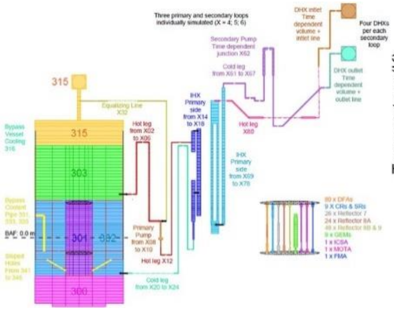


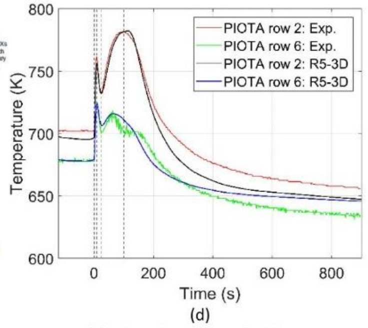


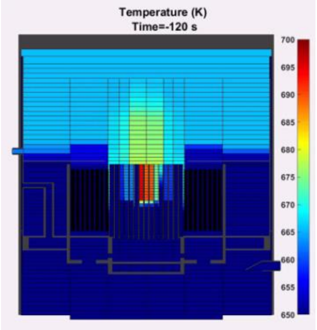


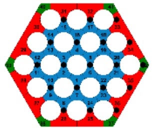
IAEA
International Atomic Energy Agency

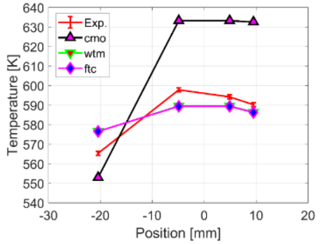
- "IAEA CRP Benchmark analysis of FFTF loss of flow without scram test" with a detailed multi-physics modelling based on a NK/TH coupling approach involving RELAP5-3D© and PHISICS codes
- IAEA CRP on Thermal-Hydraulic Analysis of Lead Cooled Experimental Subassembly (NACIE Tests)

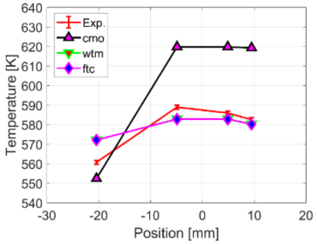


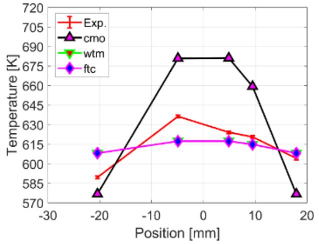












Last EU EURATOM PROJECTS IN TH AREA

We are responsible of the following tasks:

SASPAM-SA

- DBA/DEC analysis of IRIS based PWR (nuscale like developed in the same fr.)
- DBA/DEC analysis of BWRX-300 like

EASI-SMR

- TH analysis of LDR-50 reactor
- TH analysis to evaluate the re-use of SPES3 (SIET), creation of the EU-LOOP-SMR database

ANSELMUS

- ALFRED TH in support to PIRT

LESTO

- SIRIO (SIET) TH pre-test, test matrix and post-test on IC with noncondesible self-regulation (Ansaldo patent)
- ATHENA TH pre and post-test analysis

Tecnologie nucleari: presente e futuro

Standard

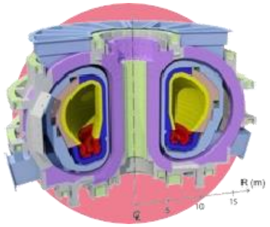
Quasi tutti i reattori oggi in funzione. Estensione della vita operativa (da 40 a 60-80 anni)

Small Modular Reactors

Piccola taglia, progettazione e costruzione modulari.

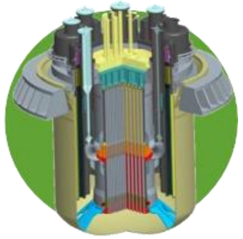
Fusione

Primo reattore (commerciale) a fusione



Evolutivi

Alcuni già operativi (Cina, UAE, Corea Sud, Russia, India). La maggioranza dei 59 reattori in costruzione nel Mondo

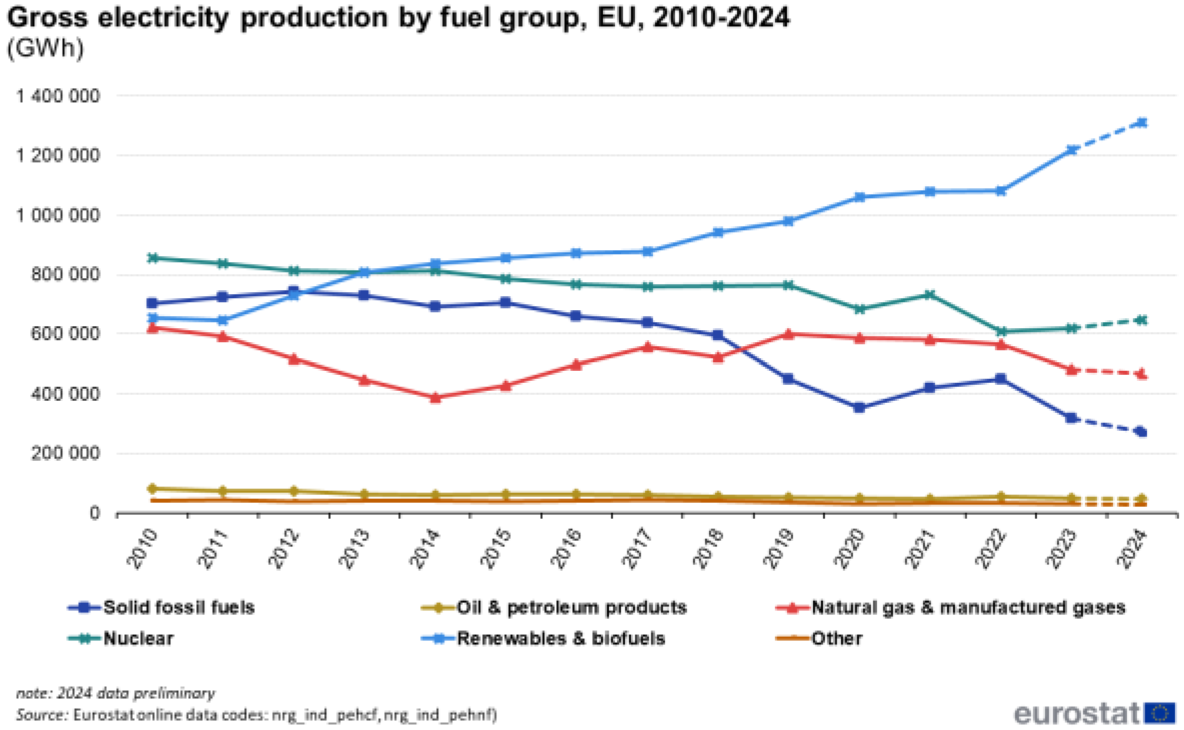


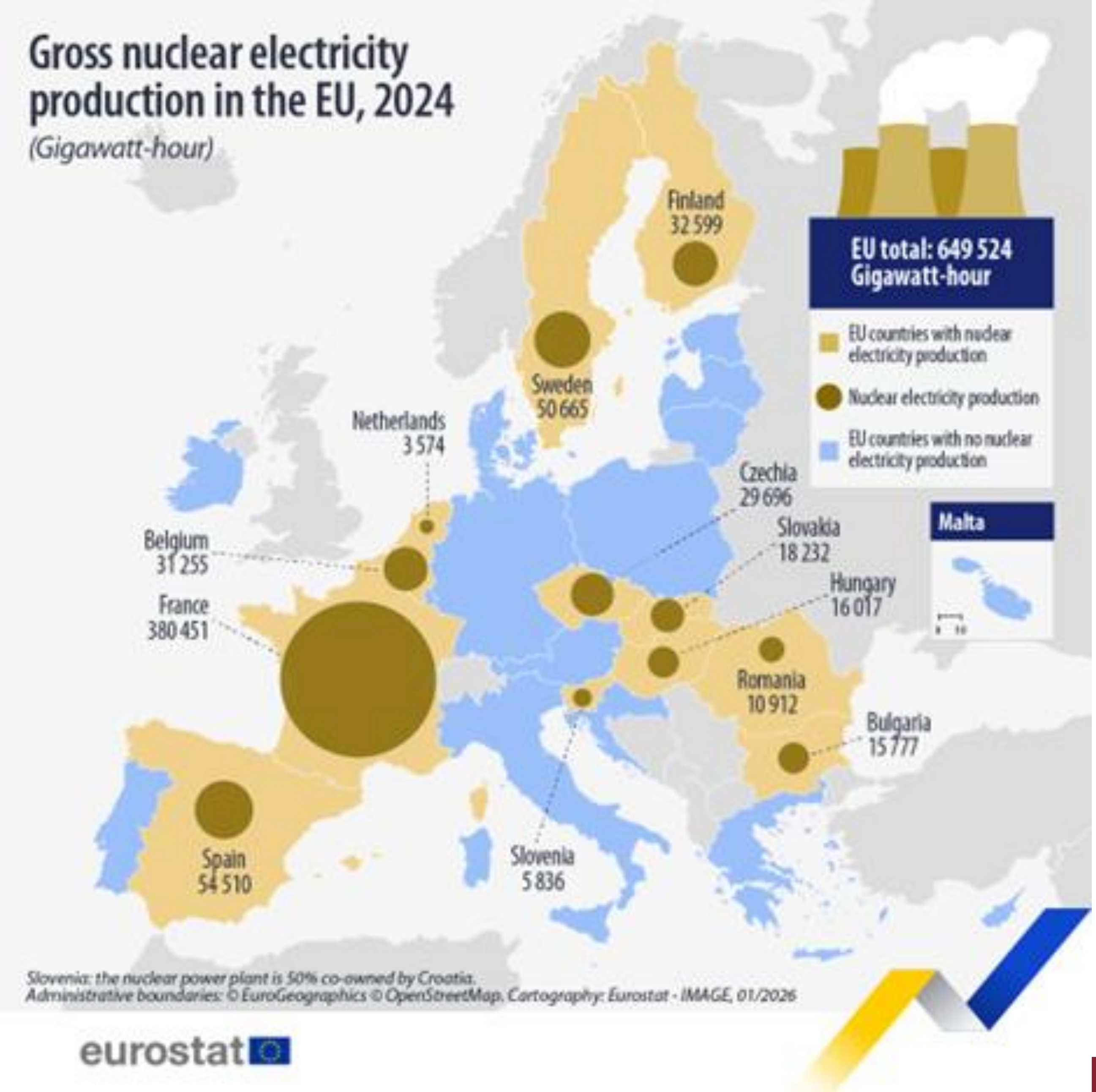
Advanced Modular Reactors

Raffreddamento a metallo liquido o a Sali fusi. Possibilità di riciclare i rifiuti a vita lunga e ad alta radioattività.

Source: M. Ricotti

Stato attuale:
GEN II e III installati in EU





Typical safety components

Feature	Active System	Passive System
Energy Source	External (Grid, Battery, Fuel)	Internal/Natural (Pressure,Gravity, Heat)
Components	Pumps, Fans, Sensors, Valves	Static reservoirs, geometries, materials
Failure Mode	Vulnerable to power loss	Fail-safe (Physics doesn't "break") Focus on the stability (degradated performance)
Maintenance	High (Moving parts wear out)	Low (Inspections of static integrity)

Cos’è un Sistema passivo?

- Un sistema composto interamente da componenti e strutture passive, oppure un sistema che utilizza componenti attivi in modo molto limitato per avviare il successivo funzionamento passivo.
- Nessun apporto di energia esterna (elettricità, diesel).
- Nessun impiego di segnali "intelligenti" (logica del computer).
- Nessuna azione da parte dell'operatore umano richiesta (per almeno 72 ore).
- Si basa esclusivamente sull'energia immagazzinata (gas compresso, molle, batterie) o su potenziali naturali (gravità, convezione).

- Elevata affidabilità, semplicità e funzionamento a prova di guasto.
- È un sistema che funziona senza la necessità di input di energia esterna (elettricità, carburante) o di controllo meccanico attivo (pompe, ventilatori, logica del computer).
- Fattori chiave: Funziona utilizzando le leggi fondamentali della fisica:
  - Gravità (ad esempio, caduta dell'acqua, caduta di aste).
  - Convezione (ad esempio, circolazione naturale dell'aria).
  - Conduzione/Irraggiamento (ad esempio, trasferimento di calore).
  - Differenze di pressione (ad esempio, espansione del gas).

Key Mechanism 1 — Natural Circulation (single phase or two-phase)

- **Principle:** Removes decay heat when the reactor pumps (active) oan/or normal residual heat removal fail.
- **Physics:** Relies on the density difference between hot water (in the core) and cold water (in the heat exchanger).
- **Application:** Used in the **Passive Residual Heat Removal** systems type.

Key Mechanism 2 — Gravity Injection

- **Principle:** Replacing lost coolant water (LOCA - Loss of Coolant Accident) using gravity.
- **Hardware:** Large water tanks located *above* the reactor vessel (e.g., In-Containment Refueling Water Storage Tank - IRWST).
- **Operation:** When reactor pressure drops below the hydrostatic head of the tank, check valves open automatically, and water flows down into the core.
- **Benefit:** Inexhaustible force;

NOT NEEDED FOR LMFR due to the low pressure and the presence of an external additional vessel.

Key Mechanism 3 — Accumulators

- **Context:** Used for *rapid* injection of water during a crash cooldown.
- **Design:** Tanks filled with borated water and pressurized with nitrogen gas (typically to 40-50 bar).
- **Trigger:** Held back only by a check valve. If reactor pressure drops below tank pressure, the gas expands (Boyle's Law: P1*V1=P2*V2), forcing water into the core instantly.
- **Passivity:** No sensors needed; the pressure differential itself is the "sensor."

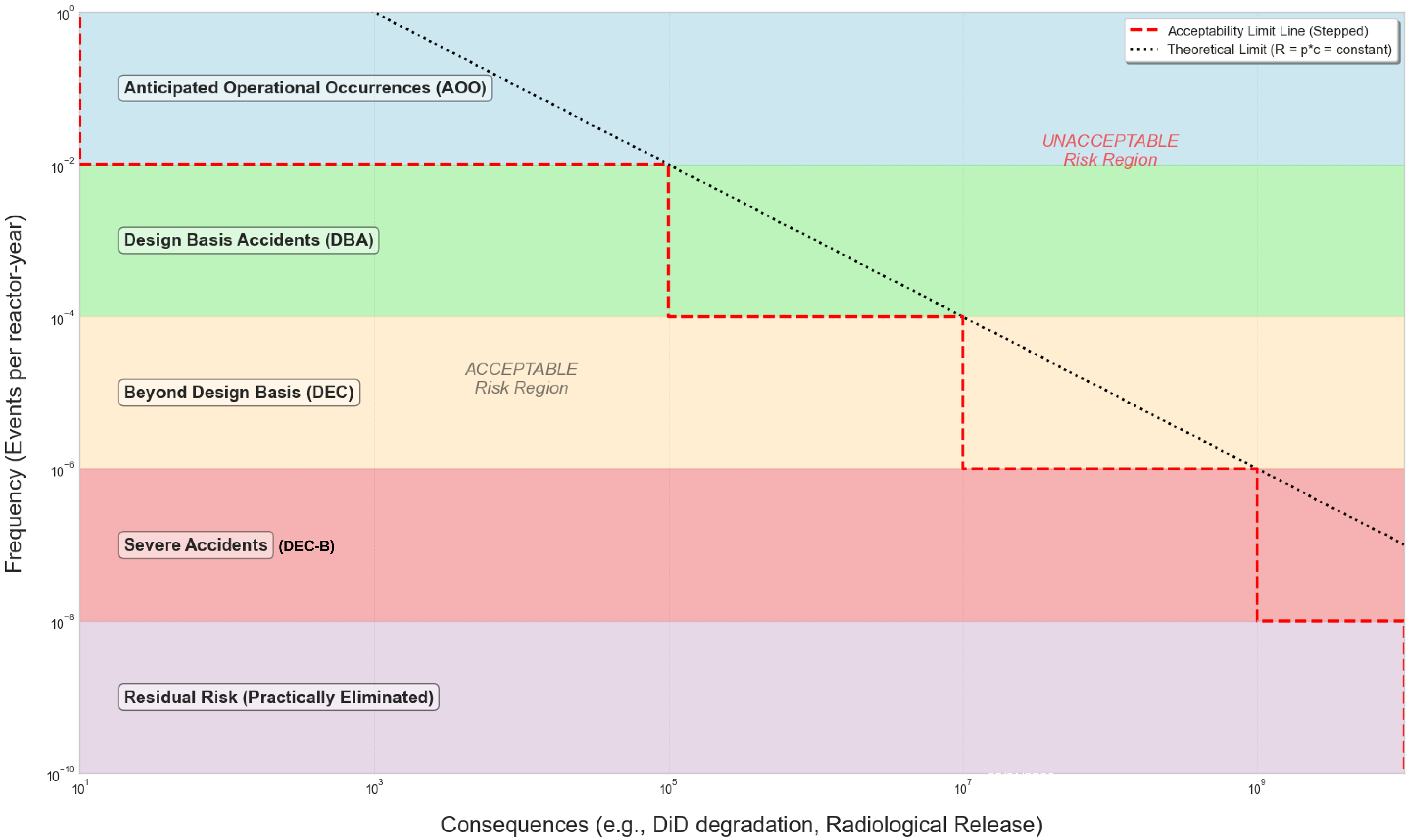
Safety approach on innovative and andvanced reactors

The "Safety by Design" Concept

- The 'Safety by Design' philosophy moves away from the traditional 'defense-in-depth' approach, which relies on active and redundant safety systems.
- Safety by design is not an added layer, but it is a fundamental characteristic derived from the reactor's physics and engineering.
- The goal is to leverage the laws of nature to create a self-stabilizing system.

- **Key Points:**
  - **Intrinsic Safety:** Harnessing self-regulating physical phenomena.
    - *Example:* Negative temperature coefficient, which reduces power as fuel temperature increases.
  - **Passive Safety:** Using systems that operate without human intervention or external power.
    - *Example:* Decay heat removal through natural convection instead of pumps.
  - **Ultimate Goal:** To make accident sequences leading to a complete core melt physically implausible or "practically eliminated." (but a core damage it is needed to study…)

Conceptual Farmer Curve with Stepped Safety Criteria (IAEA/WENRA)



Safety and Risks

- Accident History

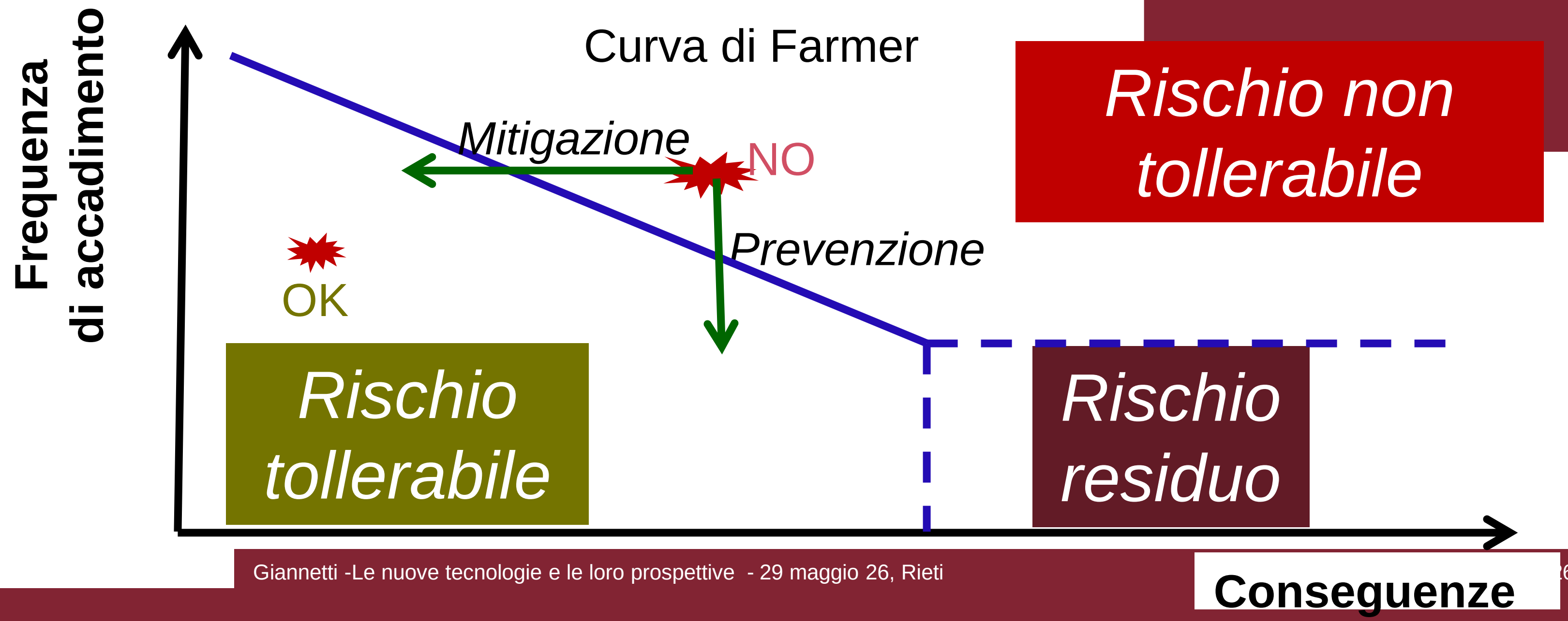
- Three Mile Island, Chernobyl, and Fukushima.

- Lesson learned and Modern Reactor Safety Features

- Passive safety systems and advancements.

- Risk Management

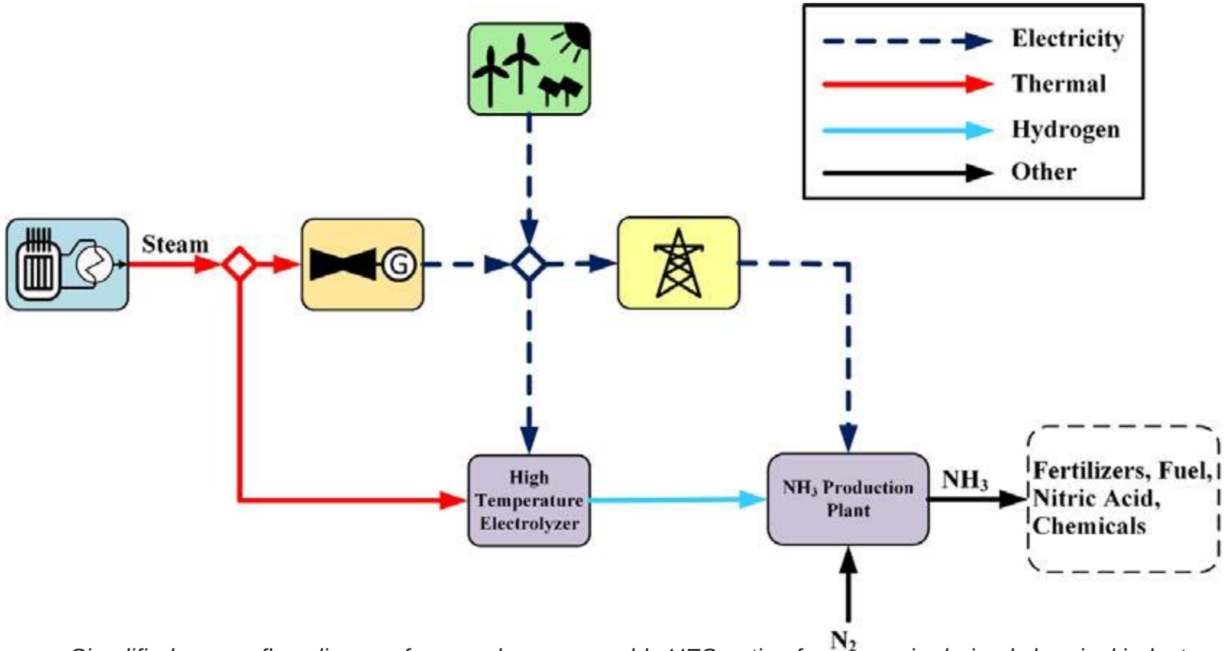
INCIDENTE	MORTI
TMI-II	0
Chernobyl	50-450
lavoratori morti nell'esplosione	2
lavoratori e pompieri morti nelle settimane successive per sindrome da acuta da radiazioni (ARS)	28
sopravvissuti all'ARS morti entro il 2006 (di cancro)	19 (5)
Stima persone morte nel tempo di cancro alla tiroide, probabilmente a causa della contaminazione del latte nelle zone circostanti.	15 (molto incerto, max 400)
Fukushima-Daiichi	0 (morti da stress correlati a evacuazione)



Hybrid Energy Systems benefits

The transition of the global energy mix to include increasing fractions of variable renewable energy sources (RESs). While introducing new challenges, this transition also presents potential synergies and opportunities for sustainable development. In particular, the proposed coupling and/or tighter integration of nuclear and renewable resources appears to be mutually beneficial. The variable nature of renewables can be well compensated by coupling with nuclear energy to provide a more equitable and inclusive energy system that is also environmentally sustainable, safe, reliable and affordable, while supporting enhanced grid resilience

- Energy independence
- Grid stability
- Optimizations of energy-intensive districts
- Hard-to-abate sectors decarbonization



Simplified energy flow diagram for a nuclear–renewable HES option for ammonia derived chemical industry

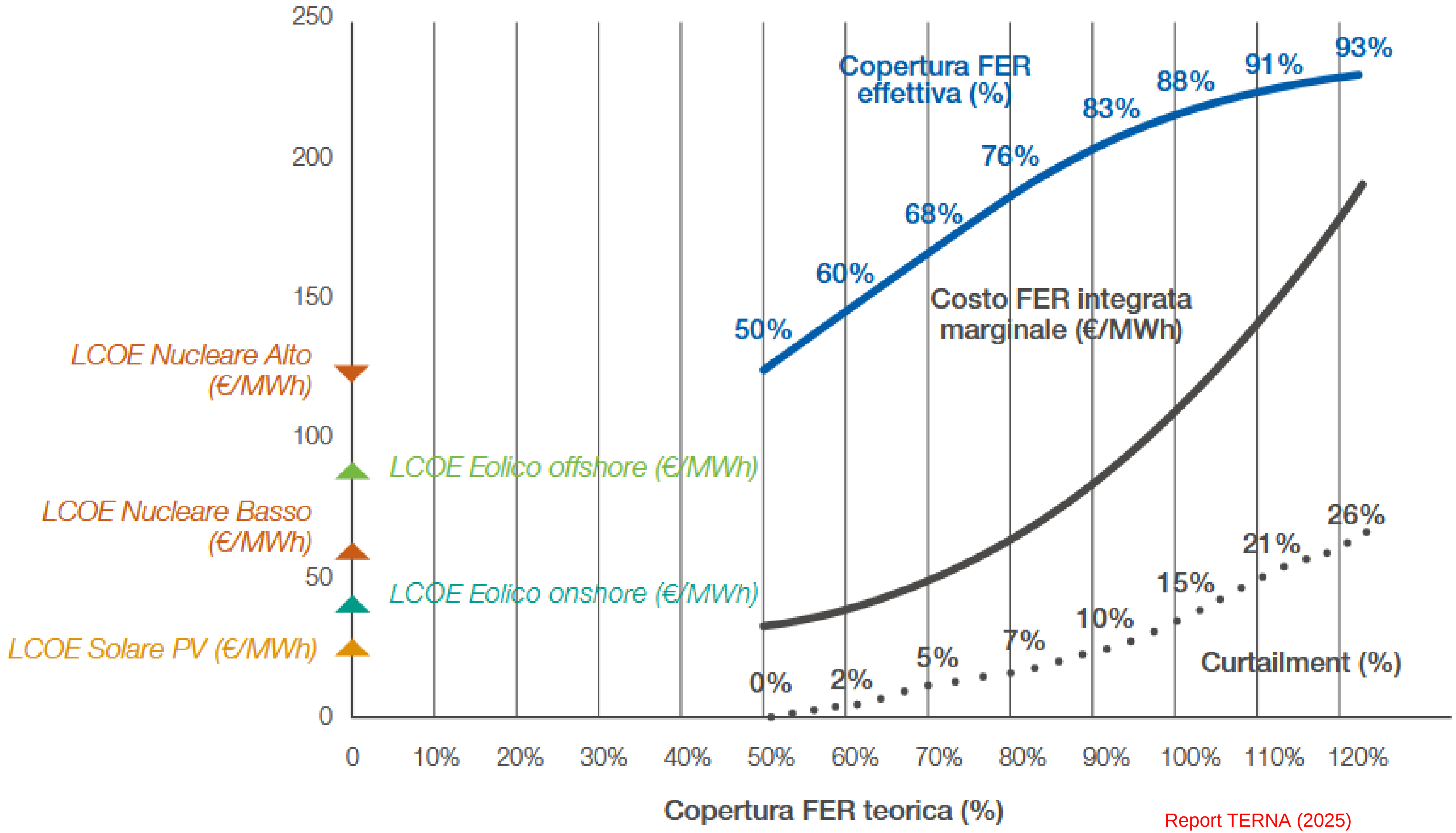
The Industrial Co-generation Advantage

Modern SMRs are designed for load-following. Furthermore, they offer a massive secondary benefit: thermal heat.

- The PNIEC models estimate that of the 8 GW installed, approximately 1.3 GW will operate in co-generation mode. During peak solar hours—when wholesale electricity prices crash—SMRs do not need to shut down. Instead, they can divert their high-temperature steam directly to heavy industry (steel, paper, chemicals), providing 16 TWh of zero-carbon thermal energy. This dual-revenue stream makes the business case for SMRs exceptionally robust.

- Integrating nuclear power into Italy's energy mix is not about replacing wind and solar, which will remain the economic backbone of the system. Instead, it is a strategic infrastructural choice. By capping the need for exponential grid expansion and seasonal storage, a balanced mix guarantees energy sovereignty, protects the landscape from extreme overbuilding, and ultimately shields consumers and industries from soaring system charges.

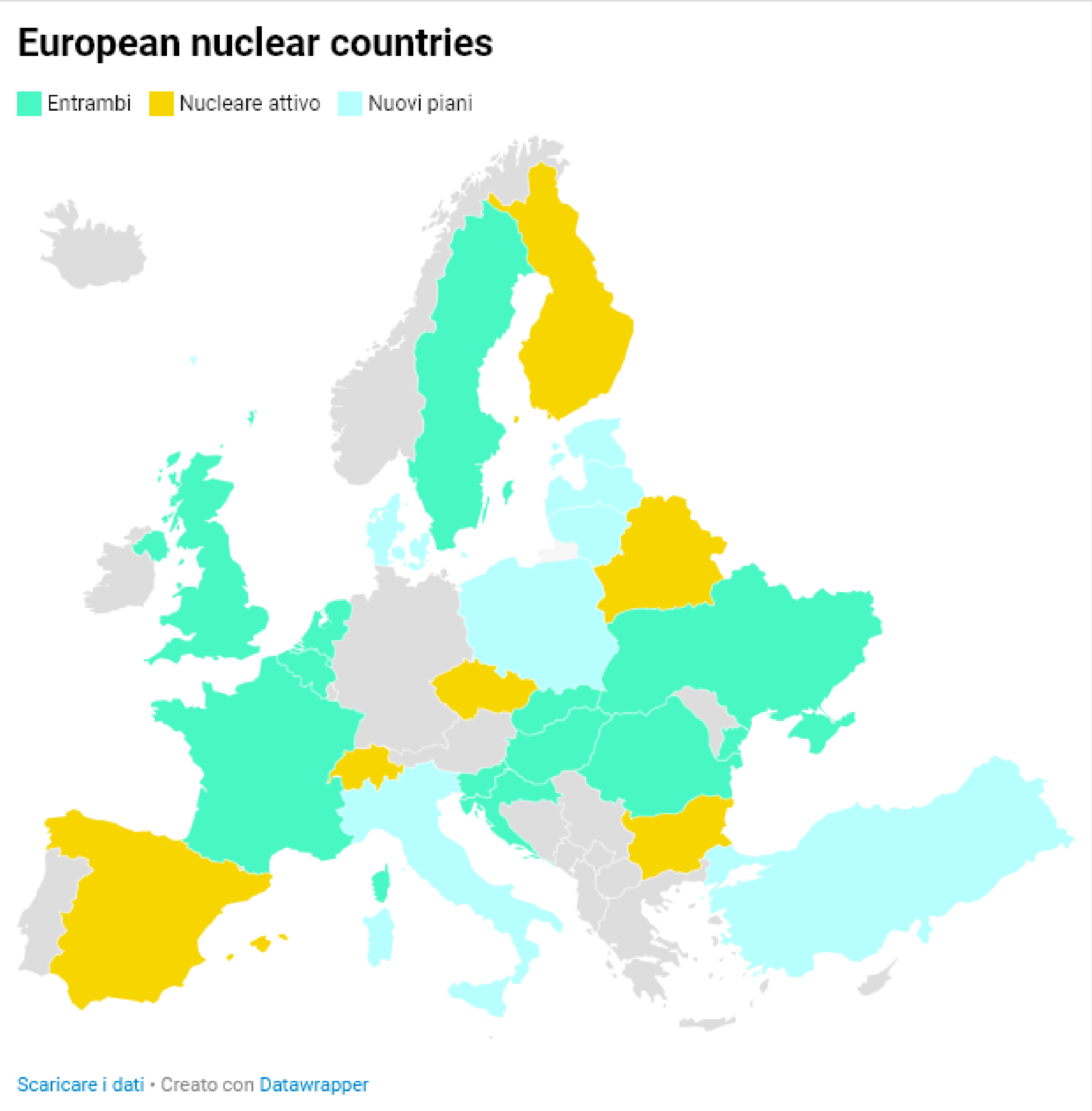
Figura 48 - Evoluzione del costo di integrazione della produzione rinnovabile in uno scenario 2050



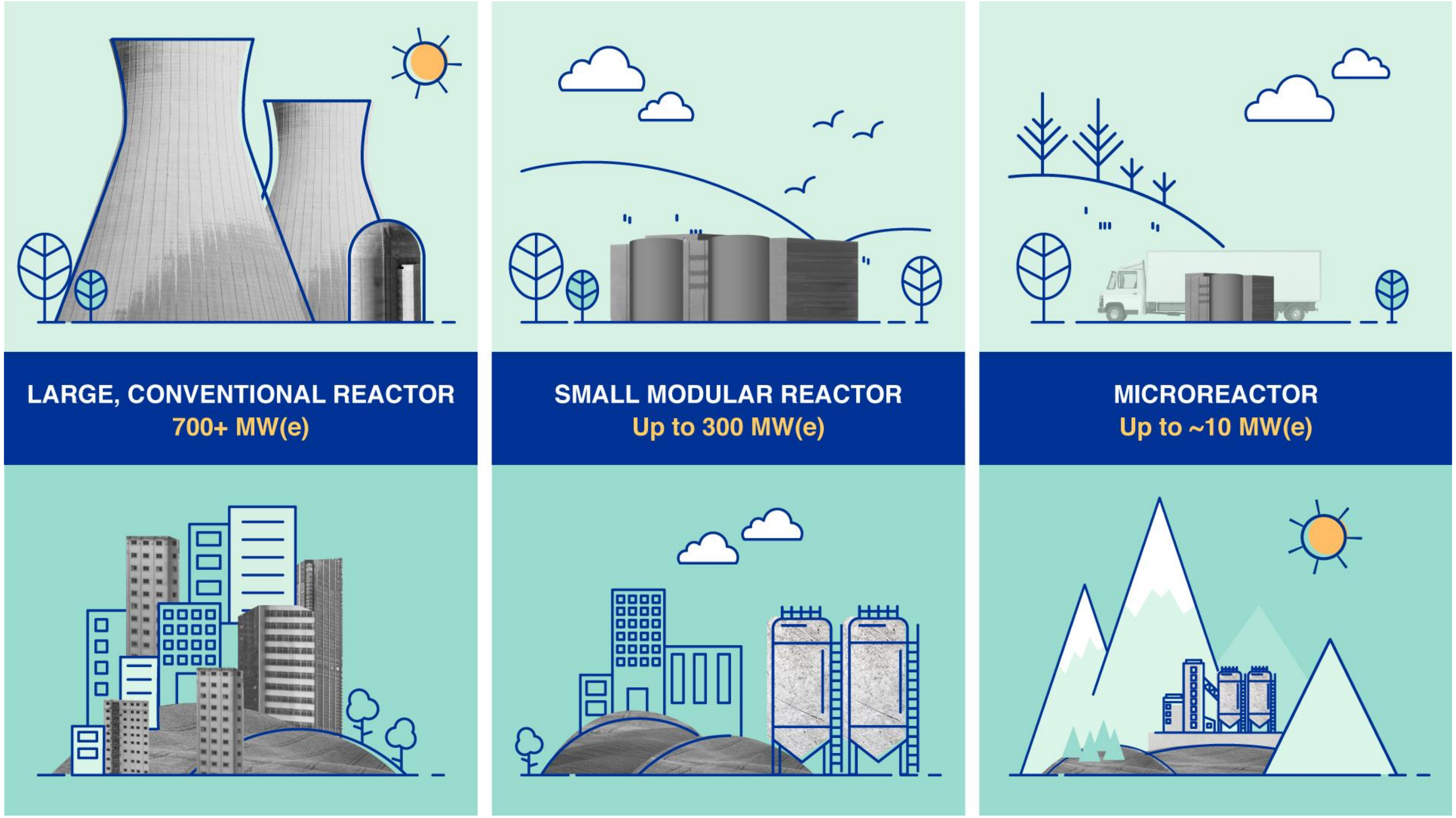
Report TERNA (2025)

Trend EU …

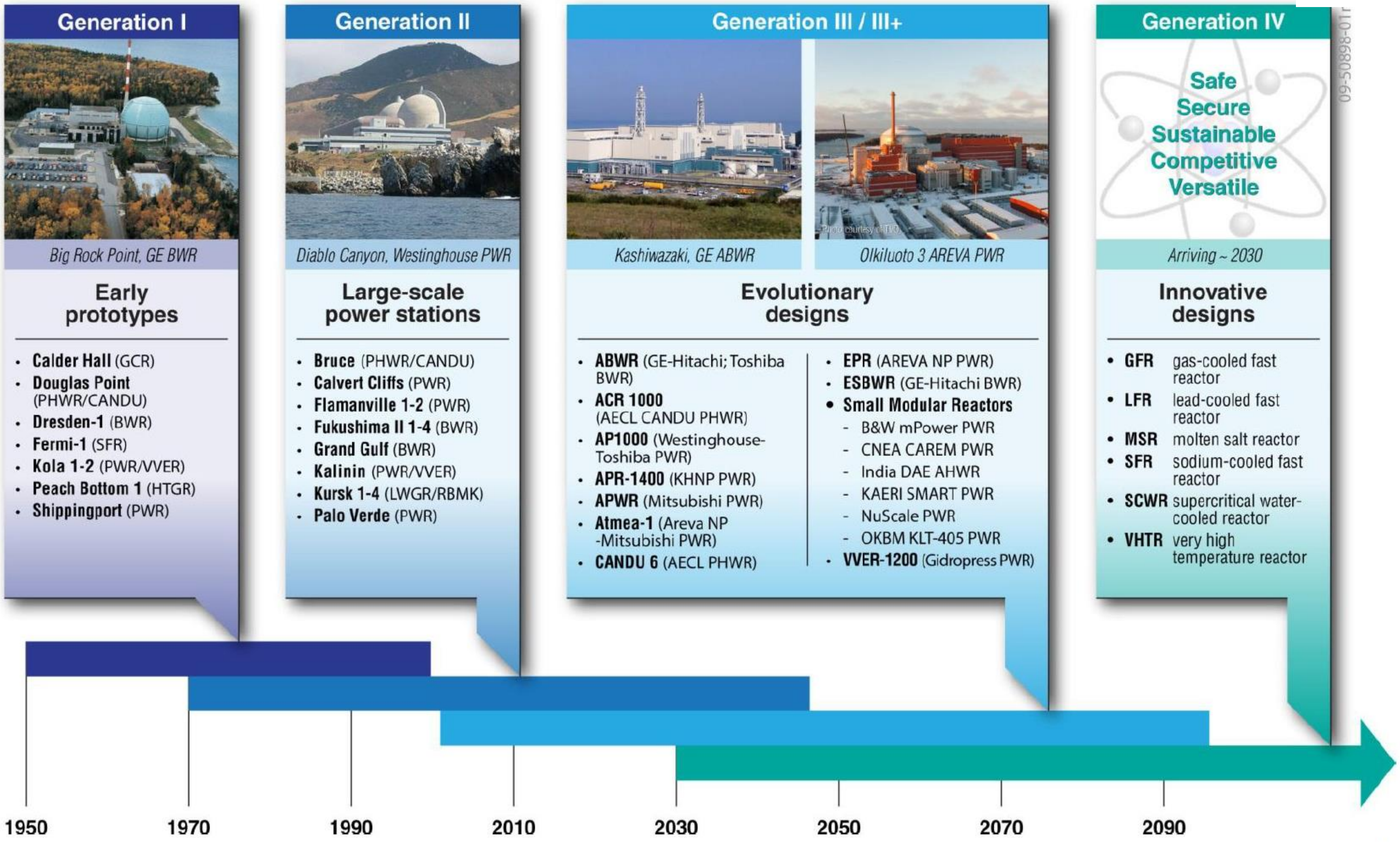
Francia	(LR, SMR, AMR)
Svezia	(LR, SMR)
Belgio	(LR, SMR)
Finlandia	(LR, SMR)
Ungheria	(LR)
Bulgaria	(LR)
Rep. Ceca	(LR)
Romania	(LR, SMR)
Slovacchia	(LR, SMR)
Slovenia	(LR)
Olanda	(LR, SMR)
Polonia	(LR, SMR, MR)



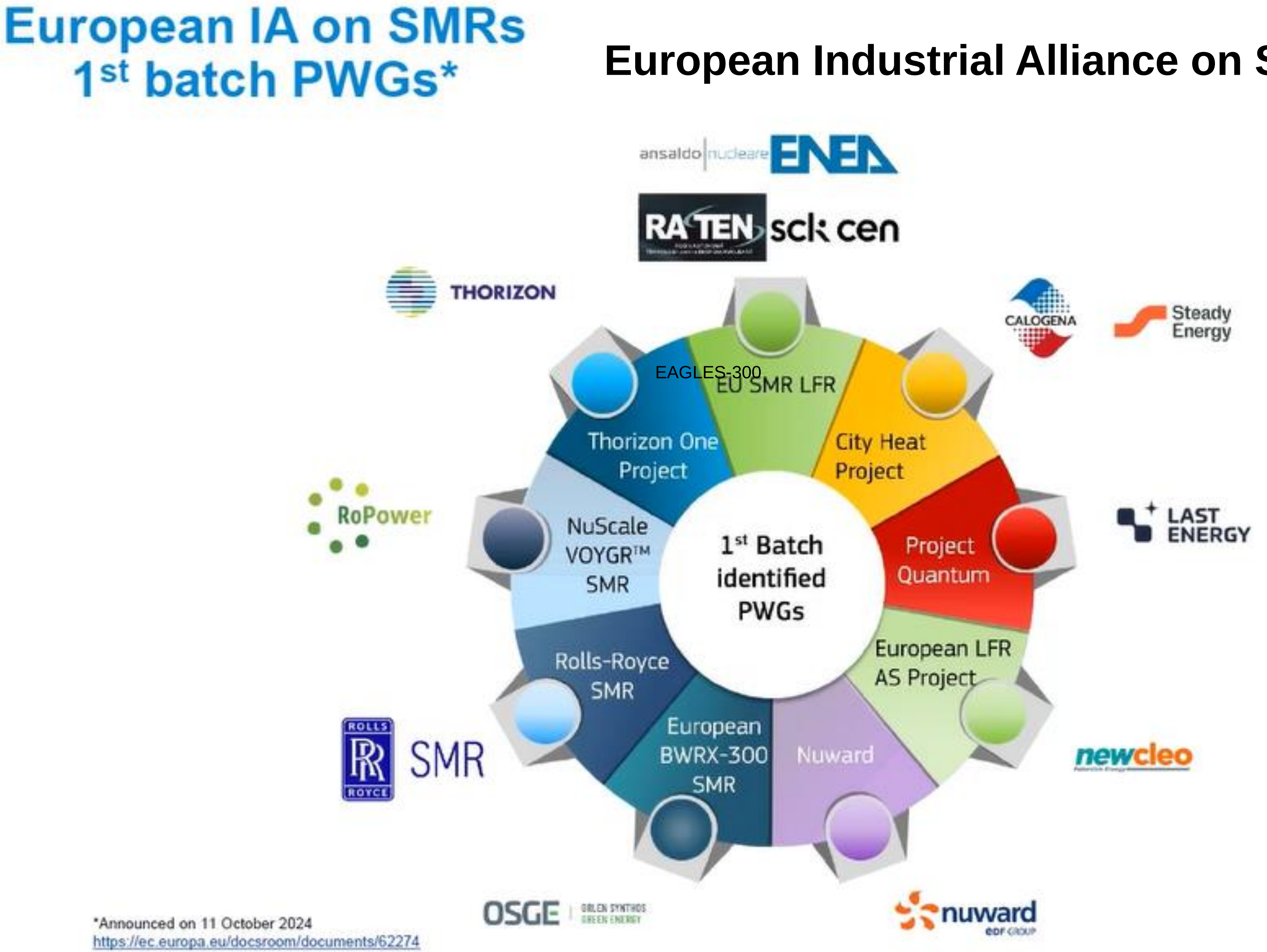
NPP size


LARGE, CONVENTIONAL REACTOR
700+ MW(e)
SMALL MODULAR REACTOR
Up to 300 MW(e)
MICROREACTOR
Up to ~10 MW(e)

Evoluzione dei reattori Nucleari



European Industrial Alliance on SMRs



Progetti selezionati nella prima valutazione

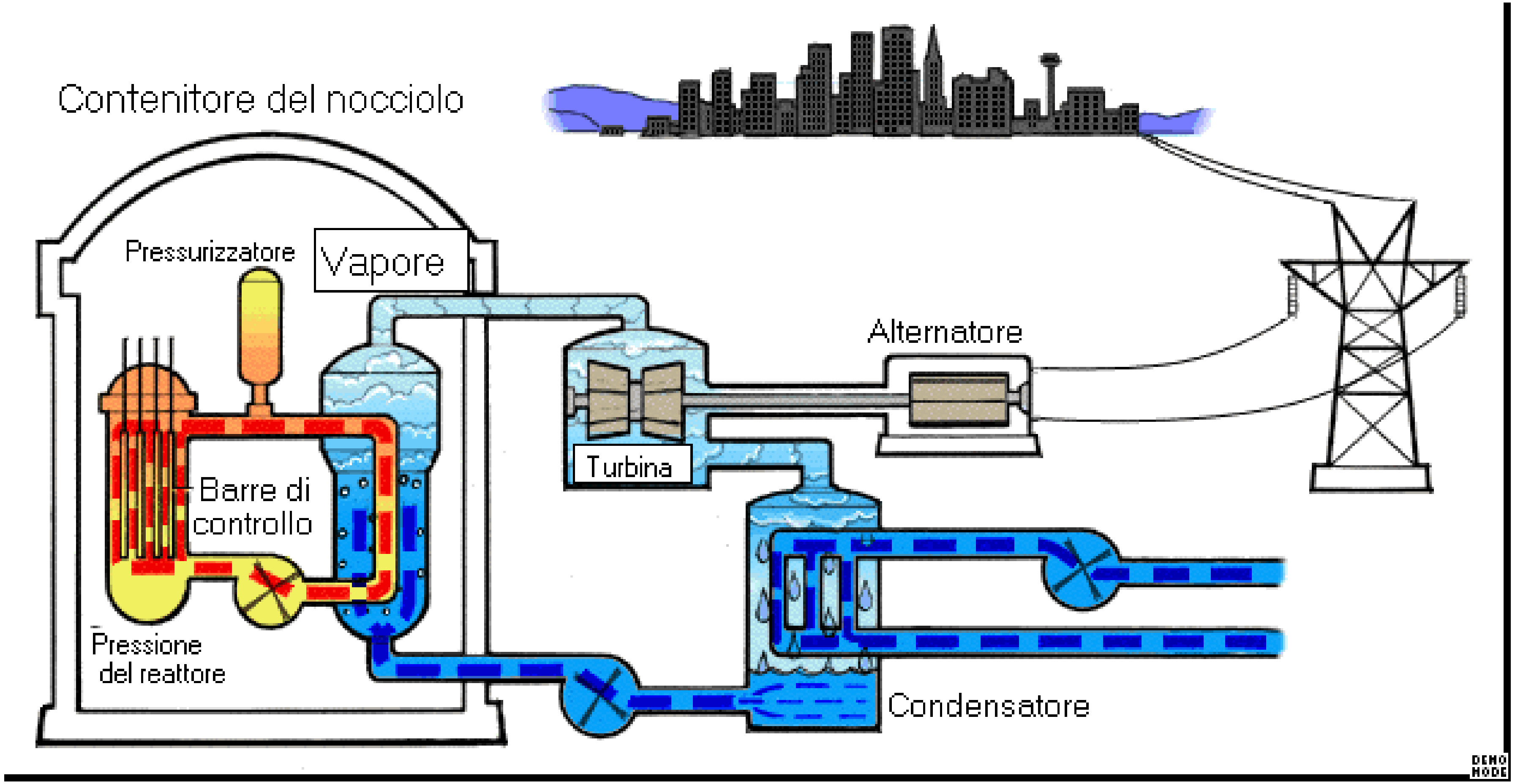
I progetti coprono 4 diverse famiglie tecnologiche:

1. Reattori ad Acqua Pressurizzata (PWR)
2. Reattori ad Acqua Bollente (BWR)
3. Reattori Veloci a Piombo (LFR)
4. Reattori a Sali Fusi (MSR)

- **PWR (5 progetti):**
  - *NUWARD, Rolls-Royce SMR, NuScale VOYGR, Project Quantum, CityHeat*
  - **Focus:** Elettricità, cogenerazione, teleriscaldamento. **Maturità:** Alta (Gen III+).
- **BWR (1 progetto):**
  - *European BWRX-300*
  - **Focus:** Elettricità flessibile (load-following). **Maturità:** Alta (Gen III+).
- **LFR (2 progetti):**
  - *EU-SMR-LFR (EAGLES-300), European LFR AS (newcleo)*
  - **Focus:** Elettricità, chiusura del ciclo, sostenibilità (Gen IV). **Maturità:** Media (Dimostratori in sviluppo).
- **MSR (1 progetto):**
  - *Thorizon One*
  - **Focus:** Elettricità, calore industriale, riciclo rifiuti (Gen IV). **Maturità:** Bassa (Concettuale/R&S).

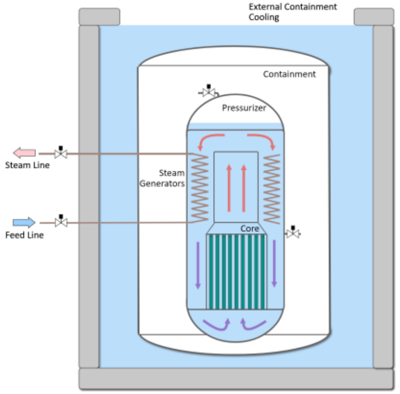
Tipologie di centrali nucleari

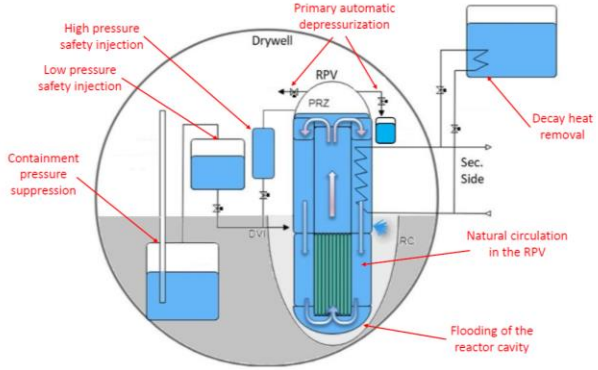
Fission Nuclear Power Plant



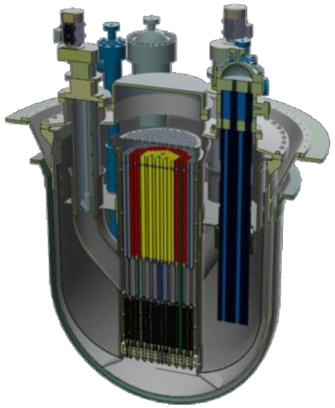
Advanced Nuclear Technologies

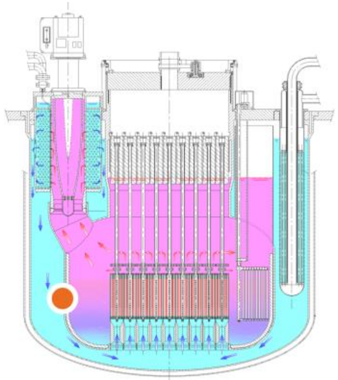
- Small Modular Reactors (SMRs)
  - Flexibility and safety, very short term



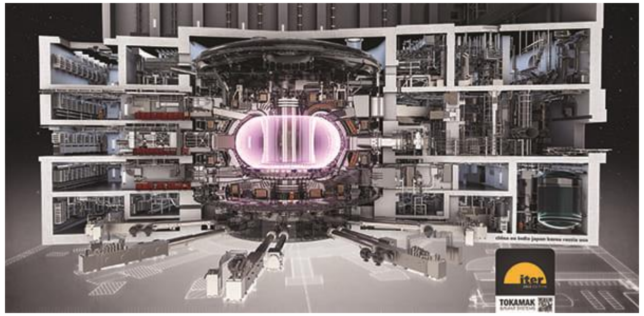


- Advanced Modular Reactors (AMRs)
  - Short term future developments (on time for decarbonization)





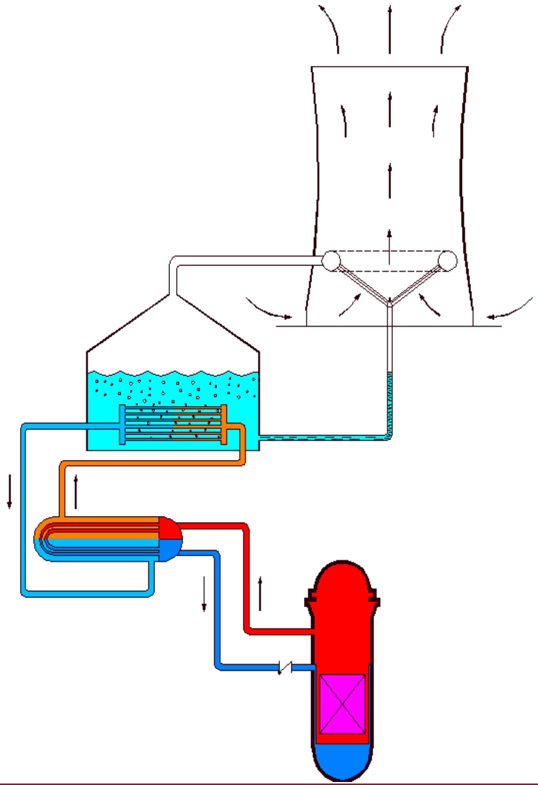
- Fusion Energy (Research)
  - Potential long-term future developments (better contribution for the final solution of the energy problems)



MARS, INHERENTLY SAFE SMR

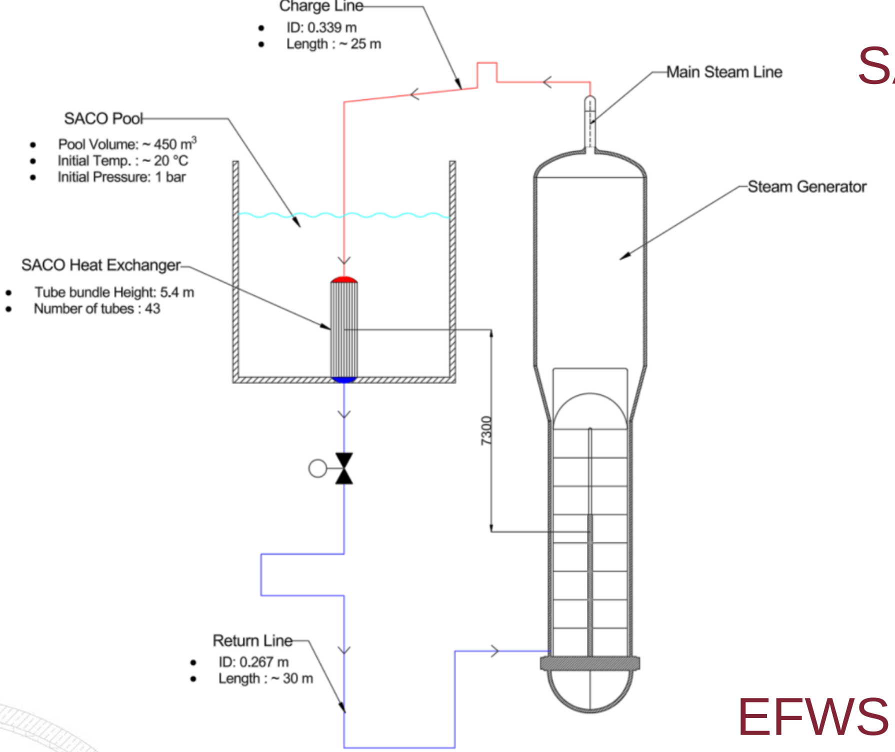
Multipurpose Advanced Reactor, inherently Safe

An "inherently safe" NPP based on plant simplification, aimed at highest reliability, with a rated power of 600 MWth
…from the '80 but quite actual

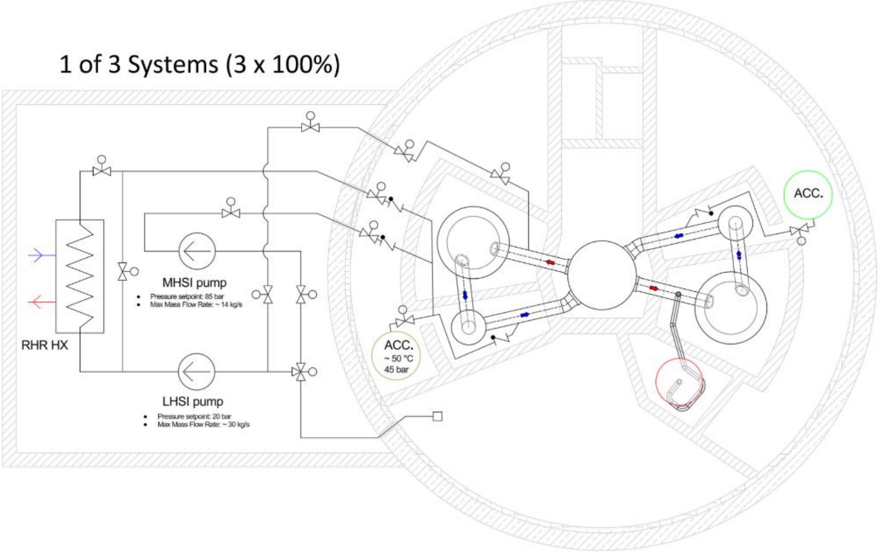


Safety systems

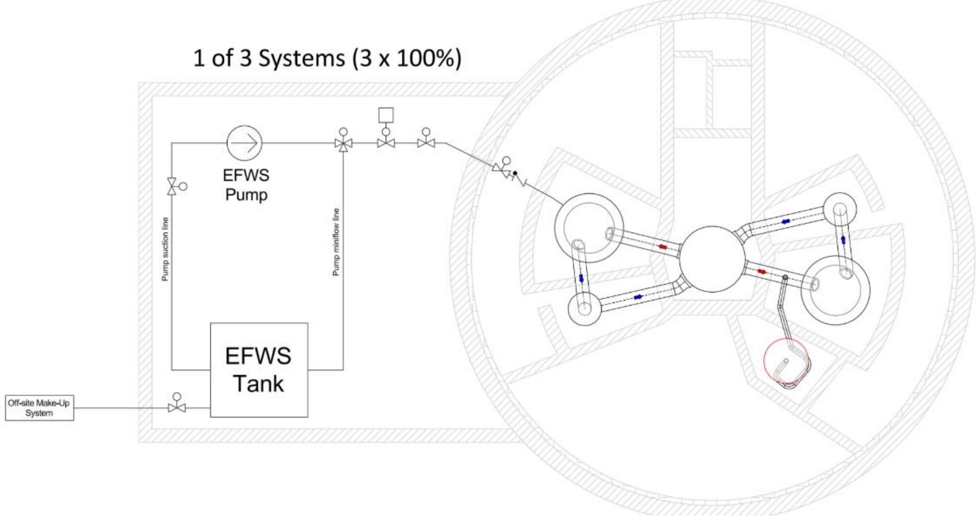
SACO



SIS/RHR



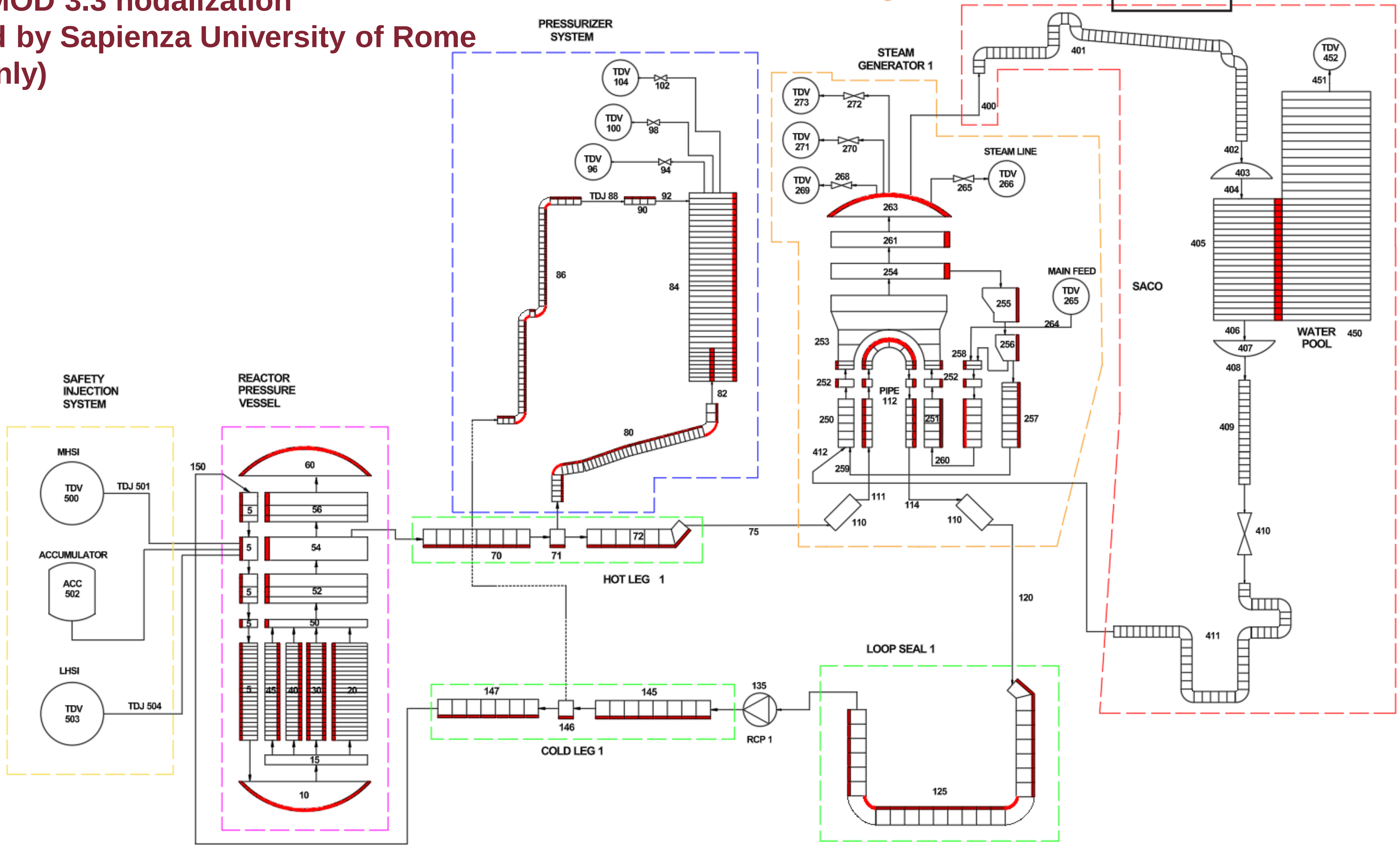
EFWS



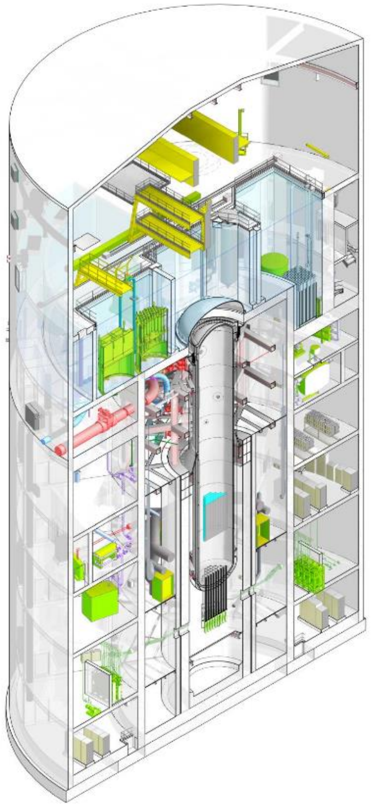
E-LOOP-SMR
RELAP5/MOD 3.3 nodalization developed by Sapienza University of Rome (Loop 1 only)

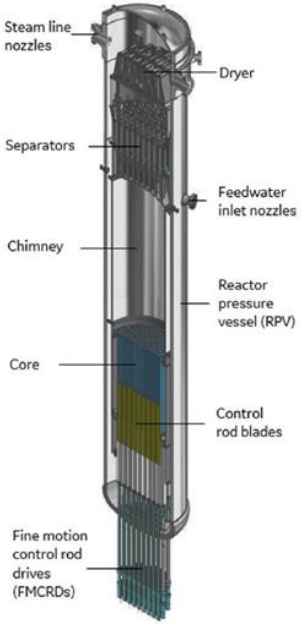
EASI SMR

Co-funded by the European Union



Design-3 configuration is based on the BWRX-300 reactor developed by GE-Hitachi Nuclear Energy.



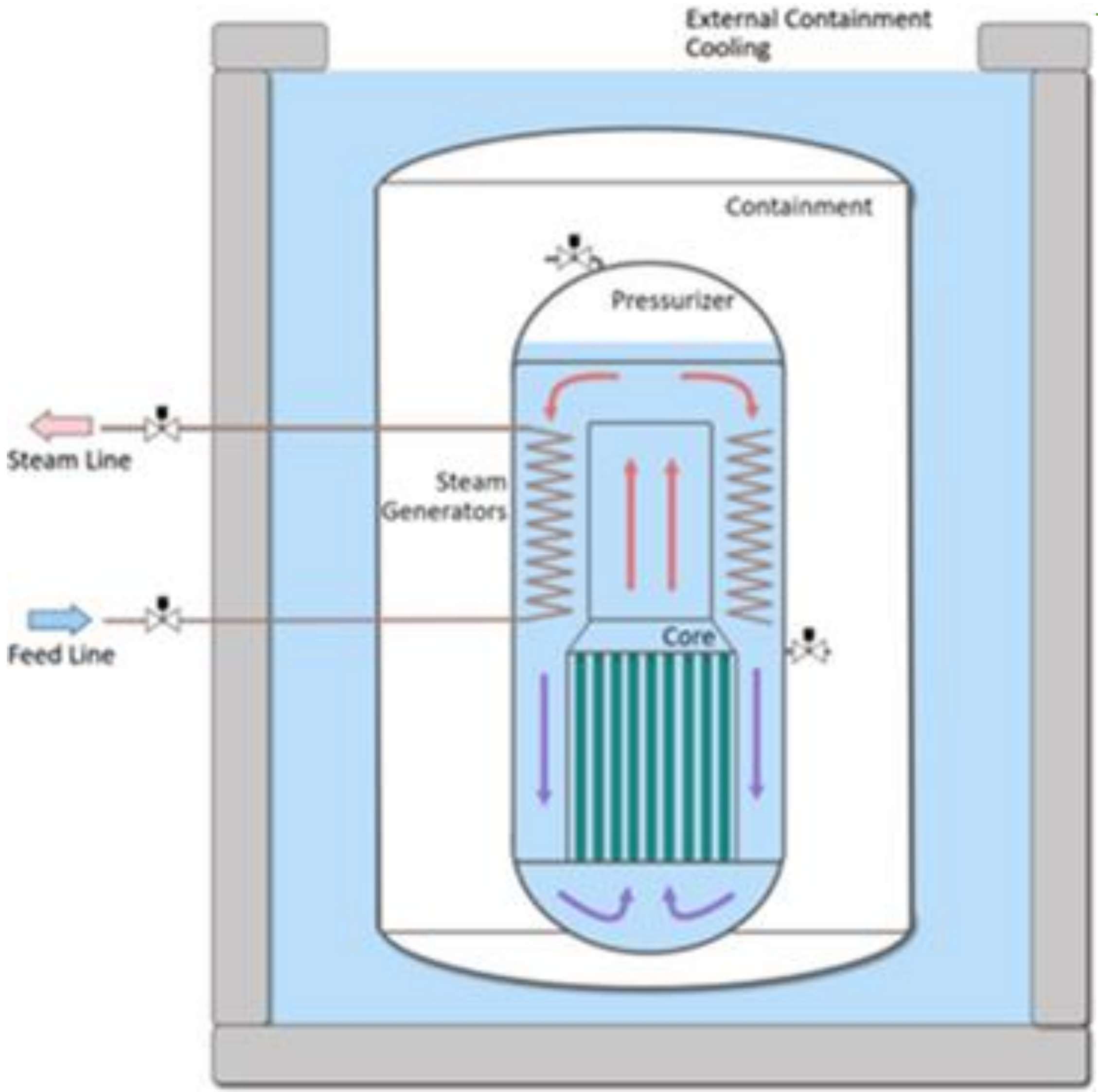


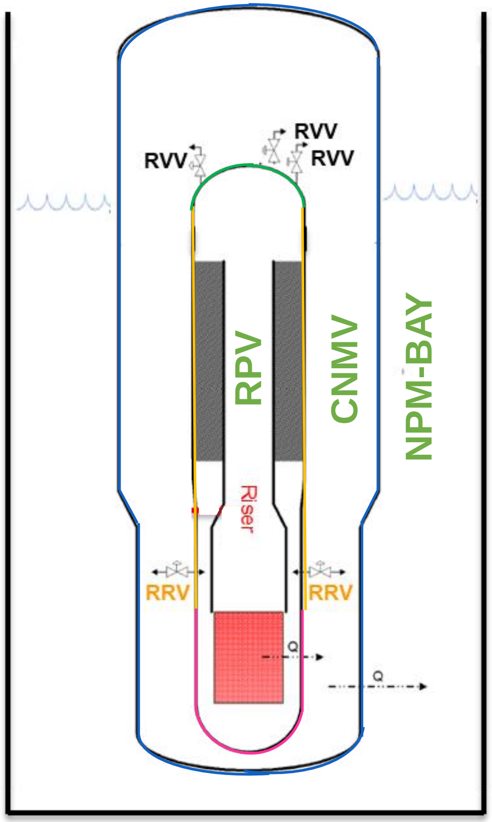
These are the main parameters used in the MELCOR model:

BWRX-300 DESIGN PARAMETERS	
Reactor Type	**BWR**
Coolant/Moderator	**Light Water**
Thermal Power	**870 MW**
Electrical Power	**290 MW**
Operating Pressure	**7.2 Mpa**
Steam Temperature	**287°C**
Primary Coolant Flow Rate	**1530 kg/s**
Primary Coolant Inventory	**1,820,000 kg**
Coolant Inlet/Outlet T	**270°C/287°C**
N. of fuel assemblies	**240**
RPV Thickness	**0.136 m**
RPV inner Diameter	**4 m**
RPV Height	**27 m**
RPV Material	**SA508 Steel**
BAF/TAF	**5.2 m/9.0 m**
Active core height	**3.8 m**
Core diameter	**3.4 m**
Refueling Cycle	**12-24 months**
Feedwater T	**228.7°C**
Feedwater Flow Rate	**487.5 kg/s**
Steam Exit Rate	**487.5 kg/s**
Return Flow	**1042.5 kg/s**

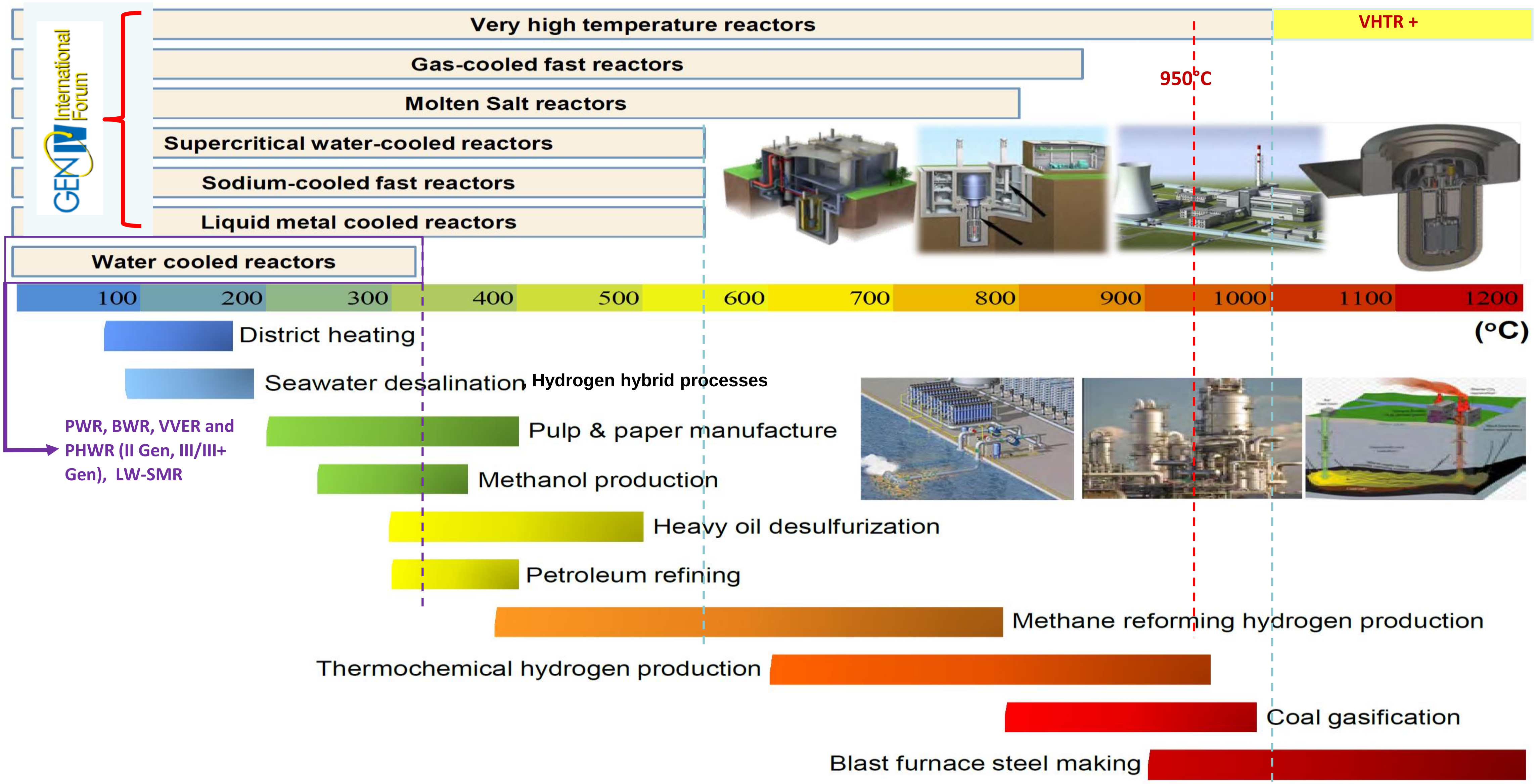
iPWR Design-1

Submerged containment, P~60 MWe,





Potenziali usi NON elettrici dei reattori nucleari di potenza



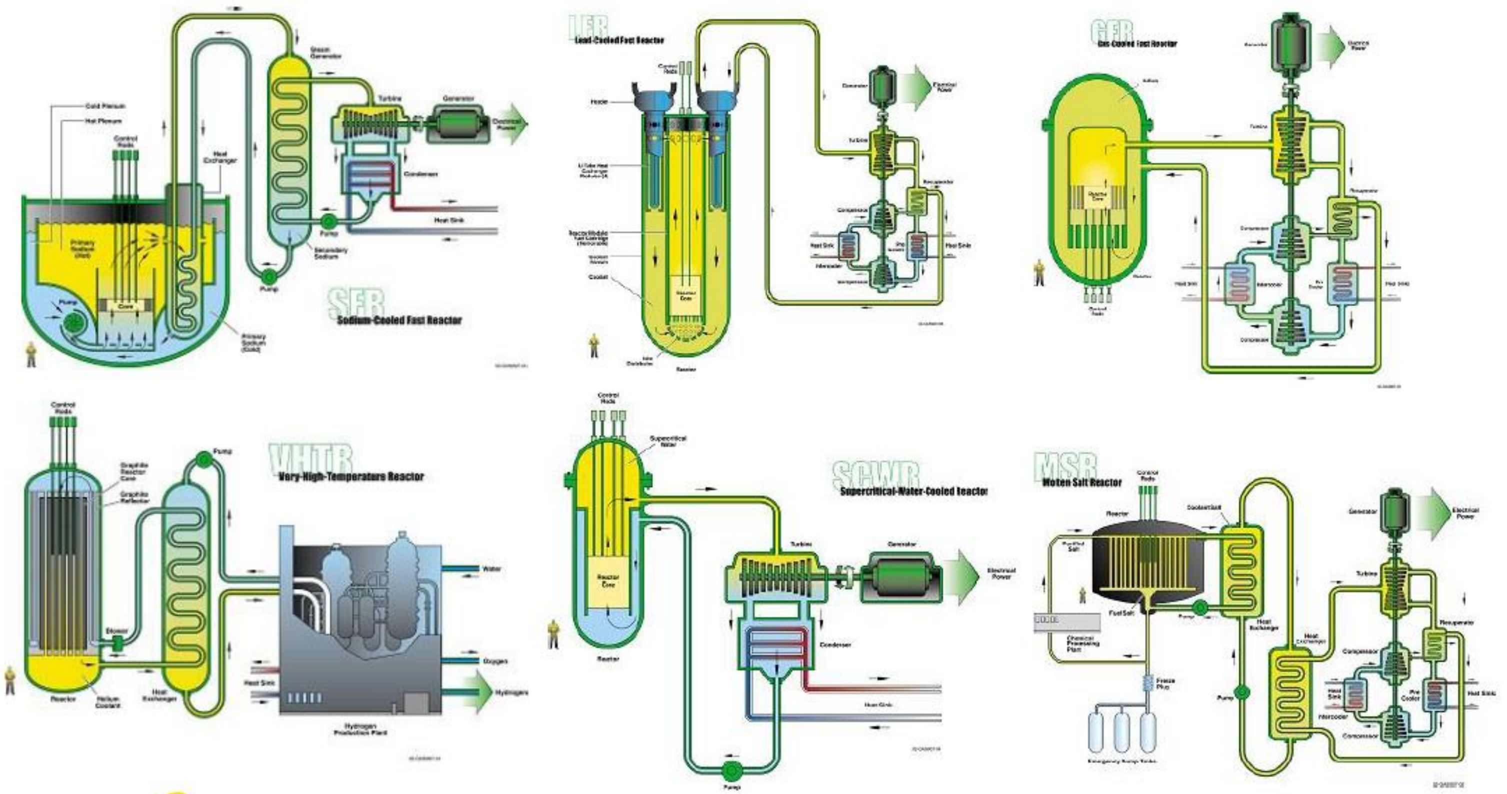
Goals for Generation IV Nuclear Energy Systems

Sustainability-1	To provide sustainable energy generation that meets clean air objectives and provides long-term availability of systems and effective fuel utilisation for worldwide energy production
Sustainability-2	To minimise and manage their nuclear waste and notably reduce the long-term stewardship burden, thereby improving protection for the public health and the environment
Economics-1	Clear life-cycle cost advantage over other energy sources
Economics-2	Level of financial risk comparable to other energy projects
Safety and Reliability-1	Reactor operations will excel in safety and reliability
Safety and Reliability-2	Very low likelihood and degree of reactor core damage
Safety and Reliability-3	To eliminate the need for offsite emergency response
Proliferation Resistance and Physical Protection	To increase the assurance that they are very unattractive and the least desirable route for diversion or theft of weapons-usable materials, and provide increased physical protection against acts of terrorism

GEN IV, reattori per il prossimo futuro

GEN IV International Forum

Generation IV Systems



Aiming at improvements in:

- Sustainability
- Economics
- Safety and reliability
- Proliferation resistance and physical protection

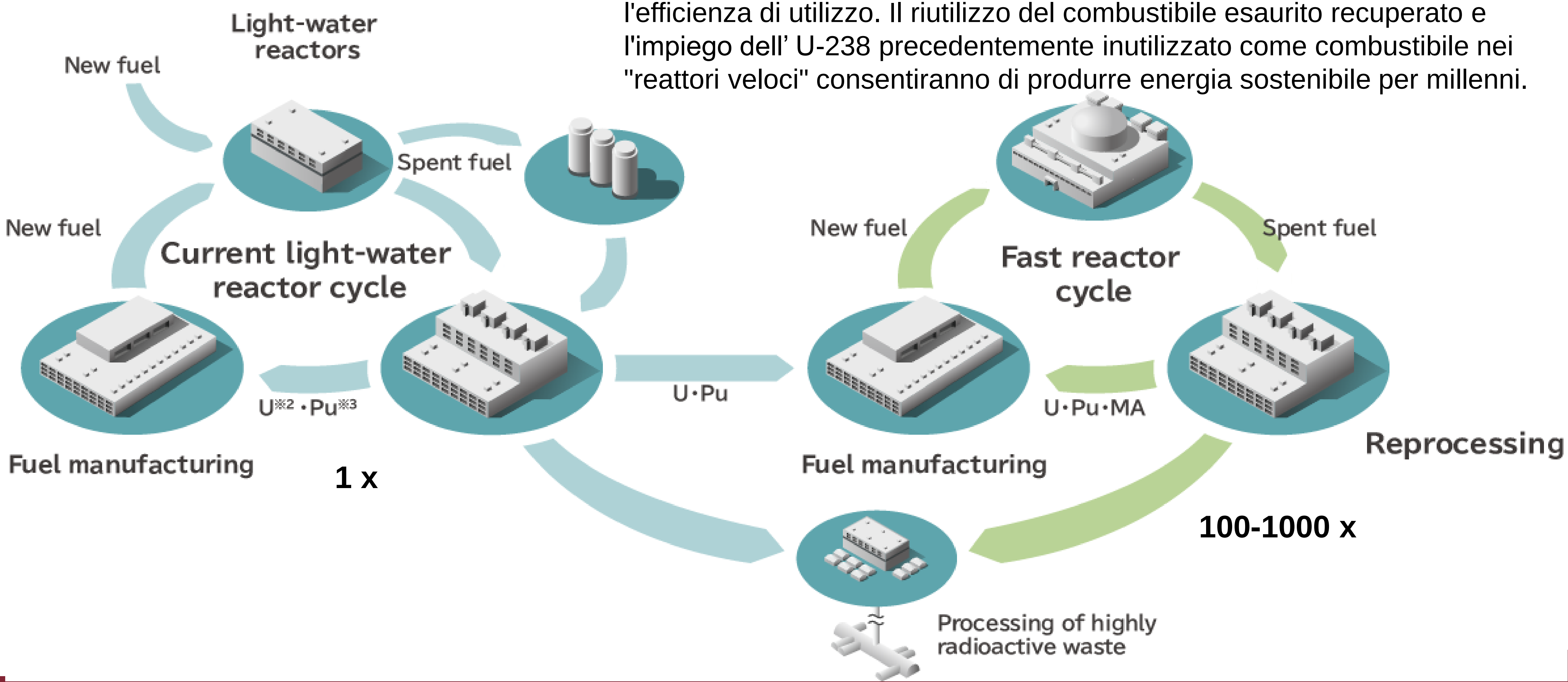
GEN IV International Forum
Expertise | Collaboration | Excellence

https://www.gen-4.org

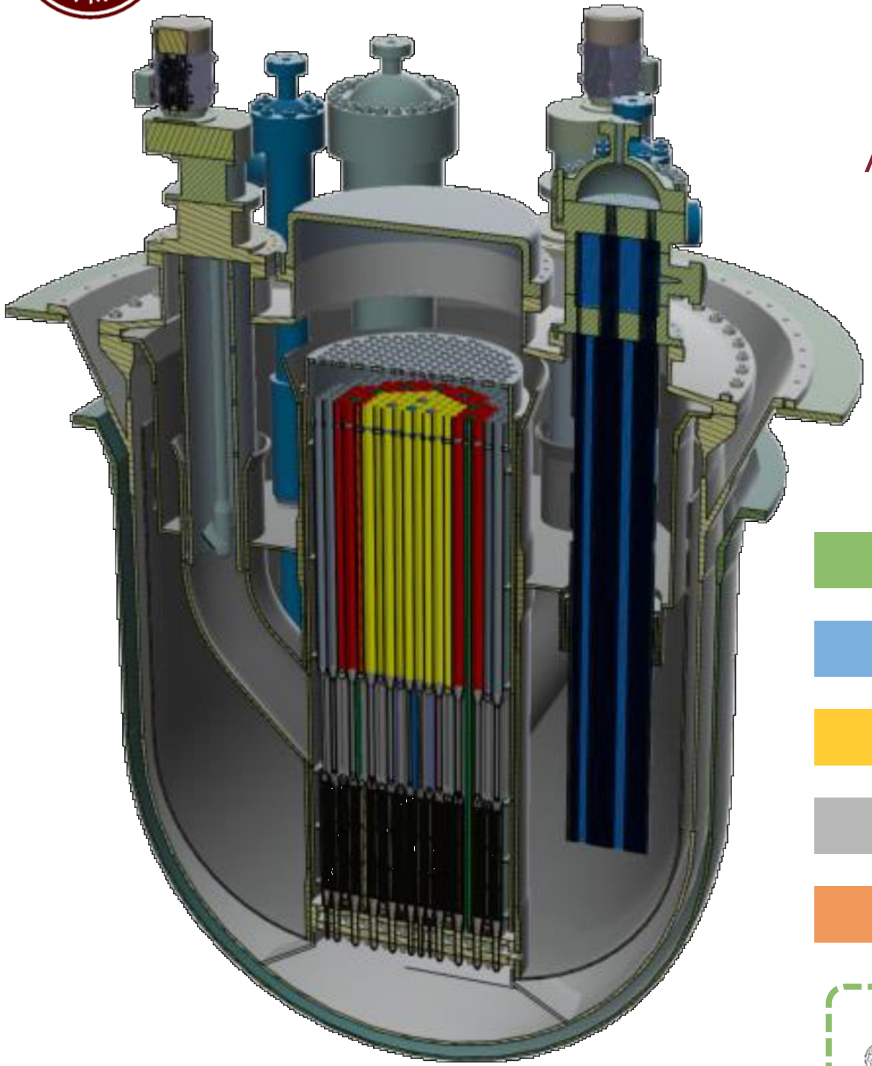
2

Ciclo chiuso per LWR e multi-riciclo per reattori veloci

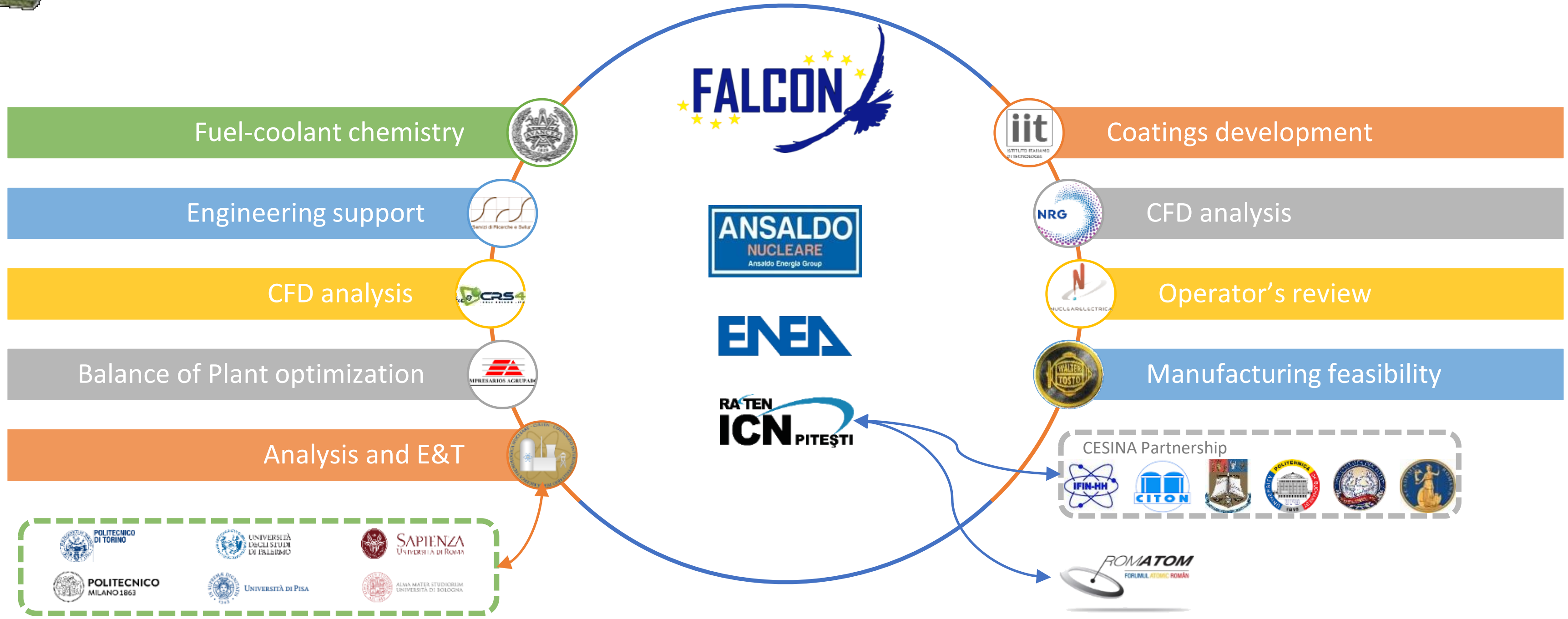
Il ciclo del combustibile dei reattori veloci permette di riutilizzare quasi tutto il combustibile in modo efficace, aumentando notevolmente l'efficienza di utilizzo. Il riutilizzo del combustibile esaurito recuperato e l'impiego dell' U-238 precedentemente inutilizzato come combustibile nei "reattori veloci" consentiranno di produrre energia sostenibile per millenni.



Advanced Lead-cooled Fast Reactor European Demonstrator
FALCON Consortium now substituted by EAGLES (ITA, Ro, Bel)

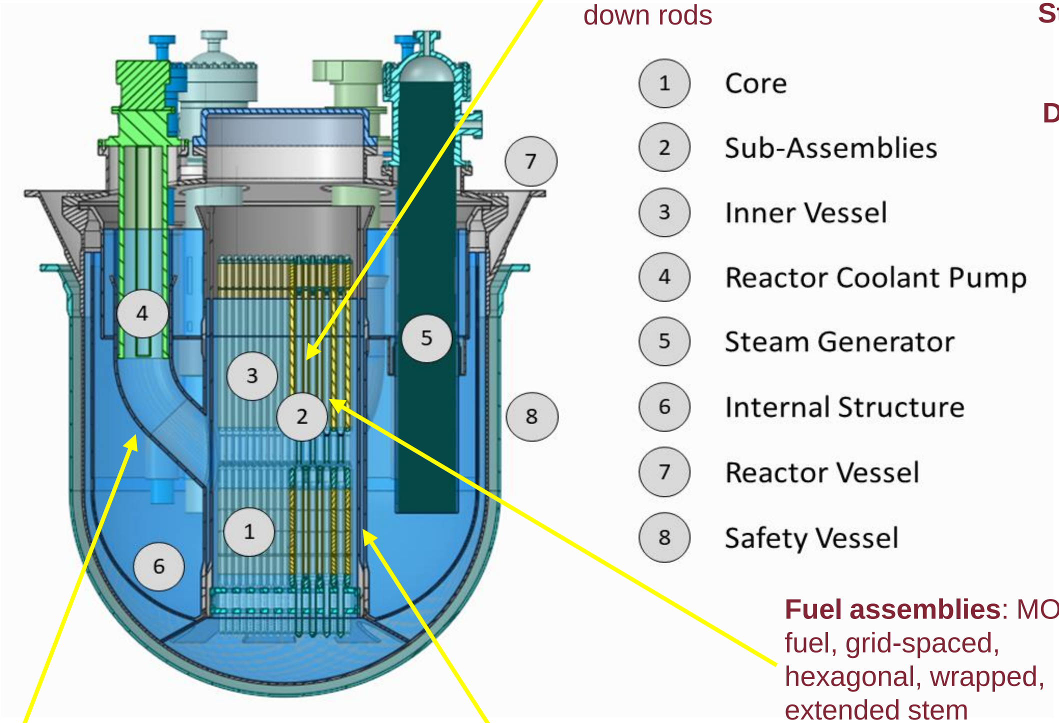


ALFRED, a 300MW **demonstration reactor**, to bridge the final gap between conducted research and industrial application, with the aim to demonstrate the same principles used in EAGLES-300, a 350MWe AM-LFR



ALFRED Layout

Reactivity control: Two diverse and redundant systems, control and shut-down rods



Fuel assemblies: MOX fuel, grid-spaced, hexagonal, wrapped, extended stem

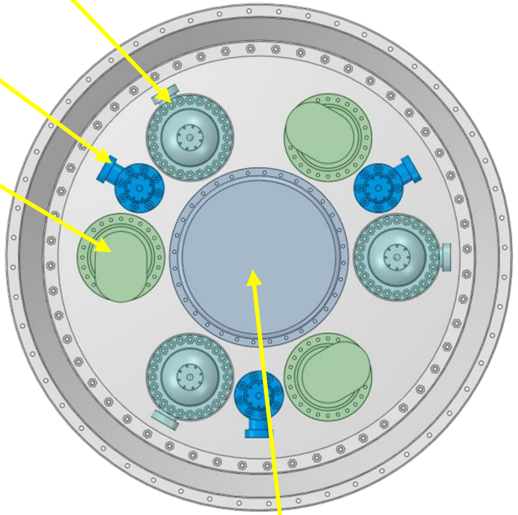
Internal Structure: no safety related, ensure pools separation and flow recirculation

Inner Vessel: safety-related, removable for out-of-vessel inspection

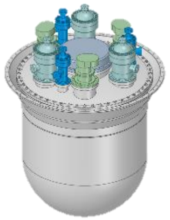
Steam Generator

Dip-cooler

Pump



Design to ensure FA handling under lead during refueling operations



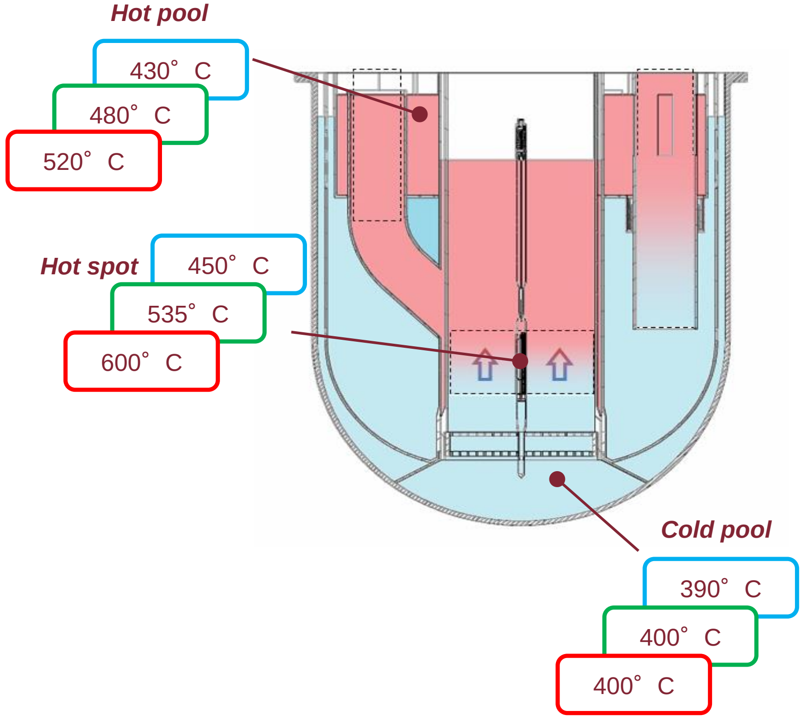
ALFRED Layout

ALFRED will serve as an intermediate step to address licensing challenges and lack of nuclear operational experience for the LFRs.

In order to overcome lacks of technology readiness and to reduce the time-to-market the development of ALFRED will be performed following a staged approach

Reactor coolant temperature

- **STAGE 1 (100 MW)**
  - Proven technology, proven materials, oxygen control, low temperature
  - Aimed at in-core qualification of PLD Al_2O_3 coating for cladding
- **STAGE 2 (200 MW)**
  - Need for FA replacement
  - Aimed at in-core qualification at higher temperature
- **STAGE 3 (300 MW)**
  - Replacement of main components (SGs, PPs, dip coolers, ...)
  - Representative of FOAK conditions for LFR deployment



LFR in Hybrid Energy Systems…

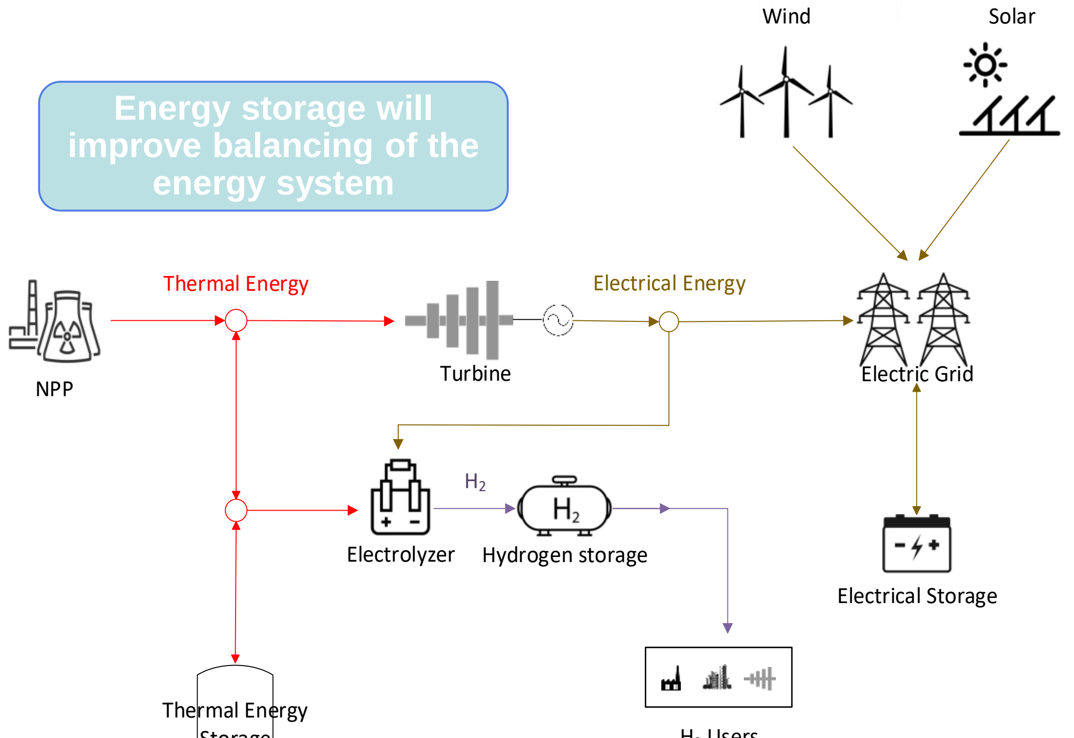
Technology	Thermodyn. Conditions	Storage Time	Efficiency	Cost	Techn. Status
Steam Accumulator	Main Steam Conditions	Hours	95% (T2T)	Very High	Commercial for CSP
Molten Nitrate Salts	290-565 ºC	Hours to Days	98% (T2T)	High	Commercial for CSP
Solid materials (e.g. concrete)	400ºC	Hours to Days	98% (T2T)	Low	Laboratory
FIRES[1][2]: NACC / NARC	550-700 ºC	Hours to Days	98% (E2T) <40% (T2E)	High	Laboratory
Hydrogen[1]: Electrolysis – Fuel Cells	-	Days	<80% (E2T) <60% (T2E)	High	Few Utility-Scale Projects - Laboratory
Hydrogen: NACC / NARC	550-700 ºC	Hours to Days	80% (E2T) 30% (T2E)	High	Laboratory
Electric Batteries	-	Days	90% (E2E)	Very High	Few Utility-Scale Projects

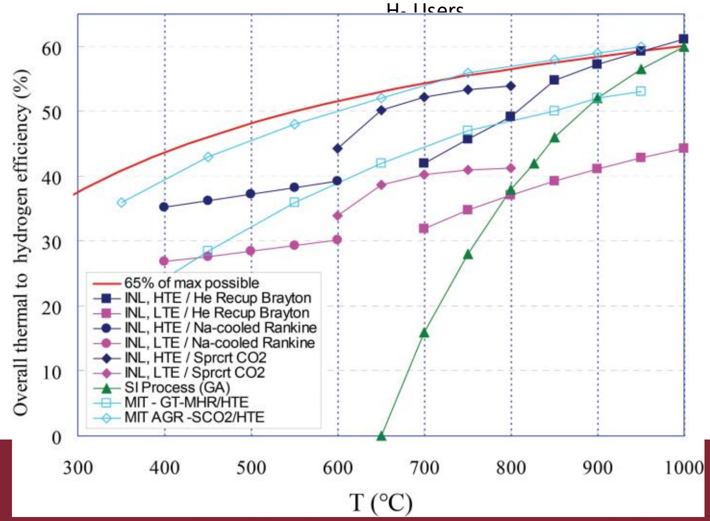
[1] https://www.osti.gov/servlets/purl/1575201

[2] https://www.tandfonline.com/doi/full/

E2E – Electric to Electric
E2T – Electric to Thermal
T2T – Thermal to Thermal

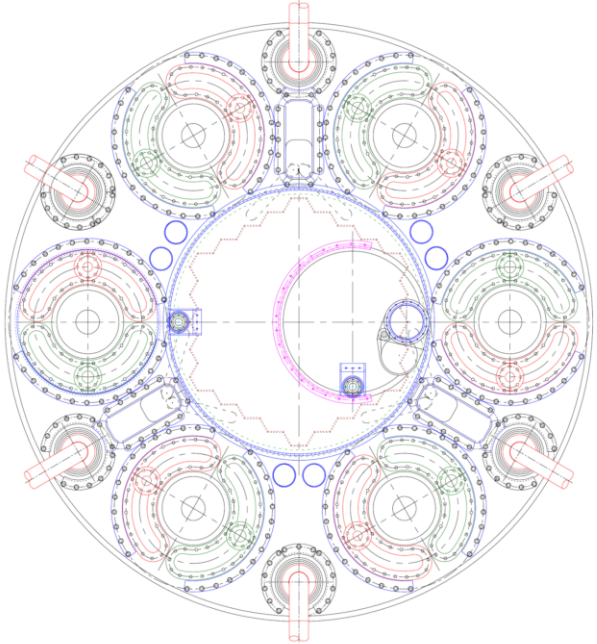
Energy storage will improve balancing of the energy system

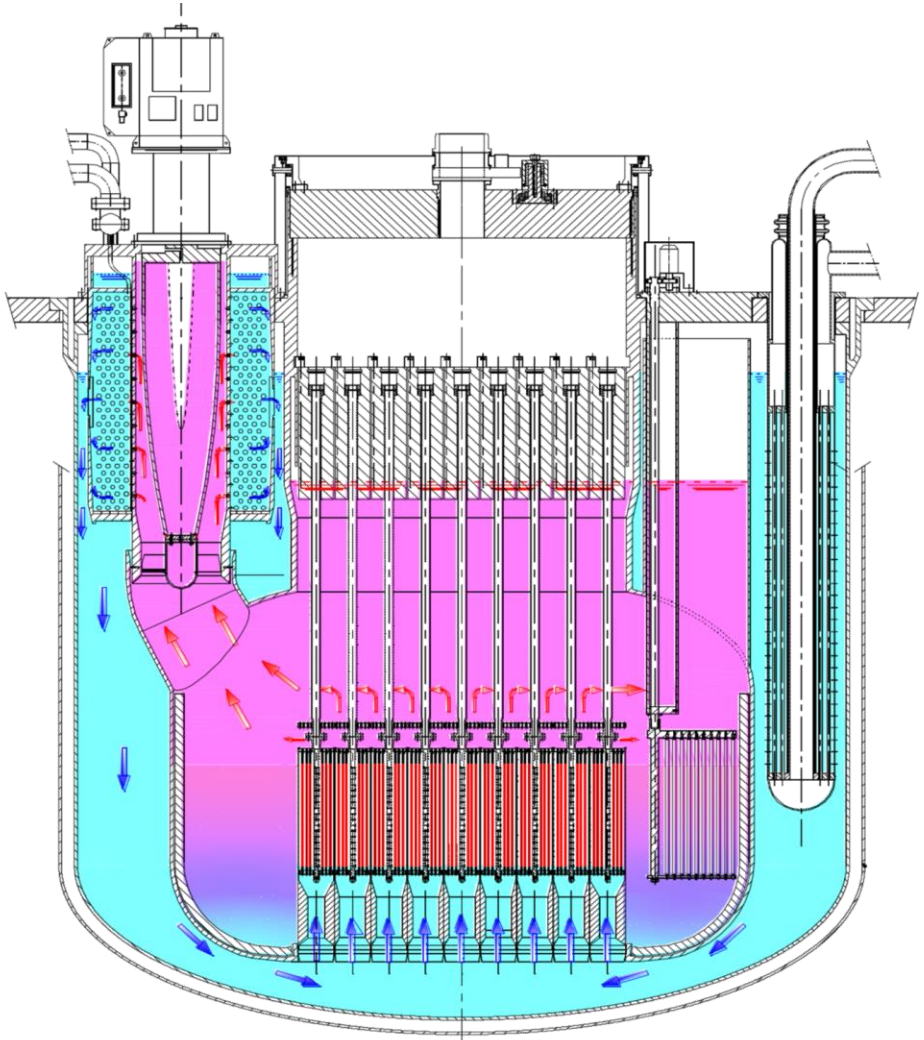




newcleo LFR-AS-200 (IT-FR-UK)

Main data	
Core power [MWth]	480
Electrical power [MWe]	200
Core inlet/outlet T [° C]	420/530
Primary loop pressure loss [bar]	1.3
Secondary cycle	Superheated steam
Turbine inlet pressure [bar]	180
Feed water/steam temperature [° C]	340/500

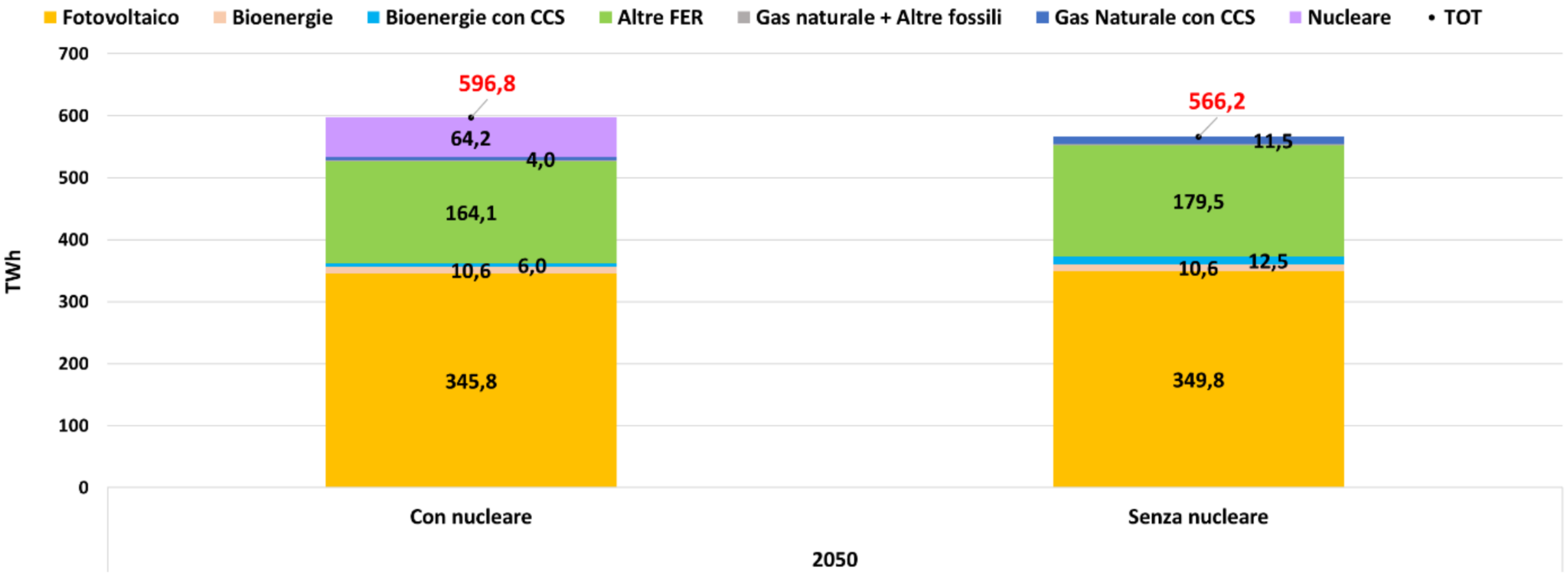




Credits: newcleo Ltd.

Conclusions

- Le nuove centrali nucleari sono considerate sostenibili e estremamente sicure, al pari delle rinnovabili
- Nucleare considerato anche in Italia, come fonte di base per garantire la sicurezza energetica, non a scapito delle rinnovabili
- Notevole riduzione dei costi di sistema per scenari ad alta penetrazione di rinnovabili



… grazie per l’attenzione

domande?

Backup slides

Design Philosophy compared with Gen II PWRs

The improvements from the GENII PWR, on which the EPR design focuses, posing special attention to security aspects, are:

- increased redundancy and separation,
- reduced core damage frequency (CDF),
- reduced frequency of large release of radioactivity (LRF),
- Mitigation of severe accidents,
- Protection of critical plant systems from internal and external events,
- increased robustness of the containment to loads RPV failure,

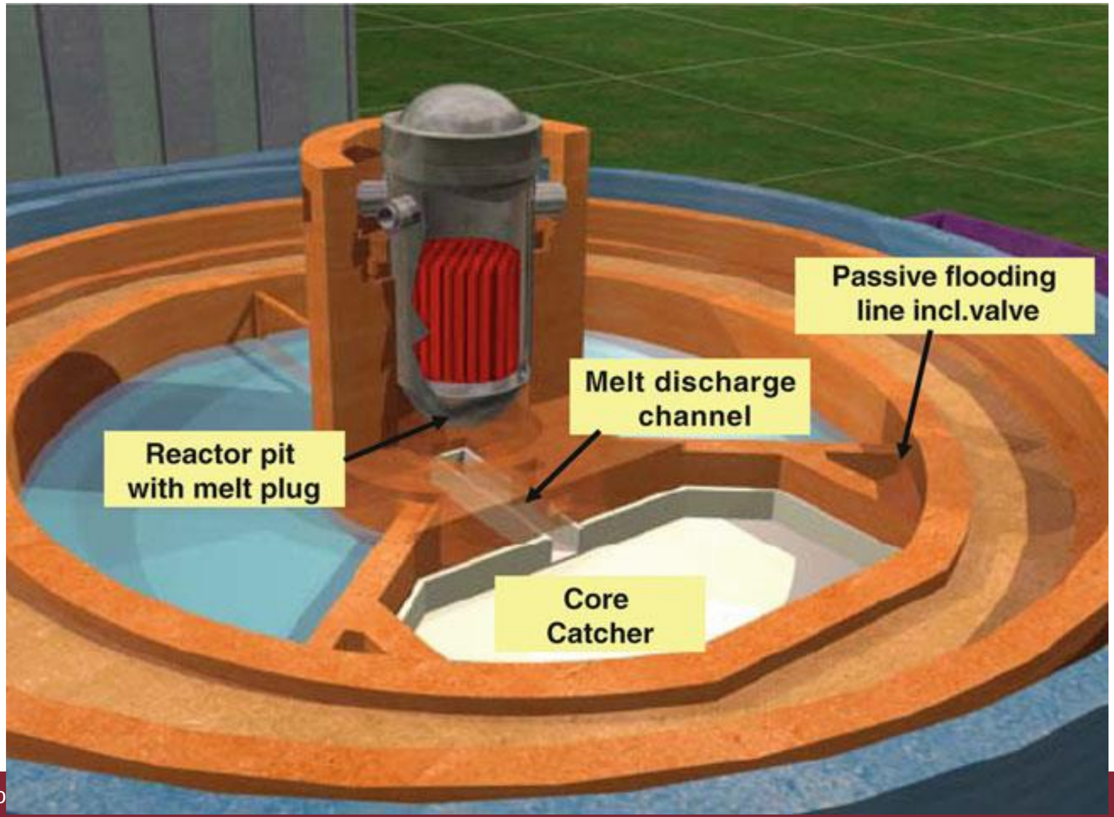
This is made possible by the application of the principle "defense-in-depth", which includes a plant behavior that aims to favorable transients, a simplification of the safety systems, and a reduction of radiological consequences following a plant malfunction

Reactor building structure

The Reactor Building consists of a cylindrical reinforced concrete outer Shield Building, a cylindrical post-tensioned concrete inner Containment Building with a 6 mm thick steel liner, and an annular space between the two structures. The thickness of the Shield Building concrete wall goes from 1.3 m below Safeguard Buildings height, to 1.8 m above it. The diameter of the dome is 66 m.

CORE Catcher

- The spreading compartment is a dead-end room which is isolated from the rest of the containment, and it is designed to be dry at the time of the melt arrival.

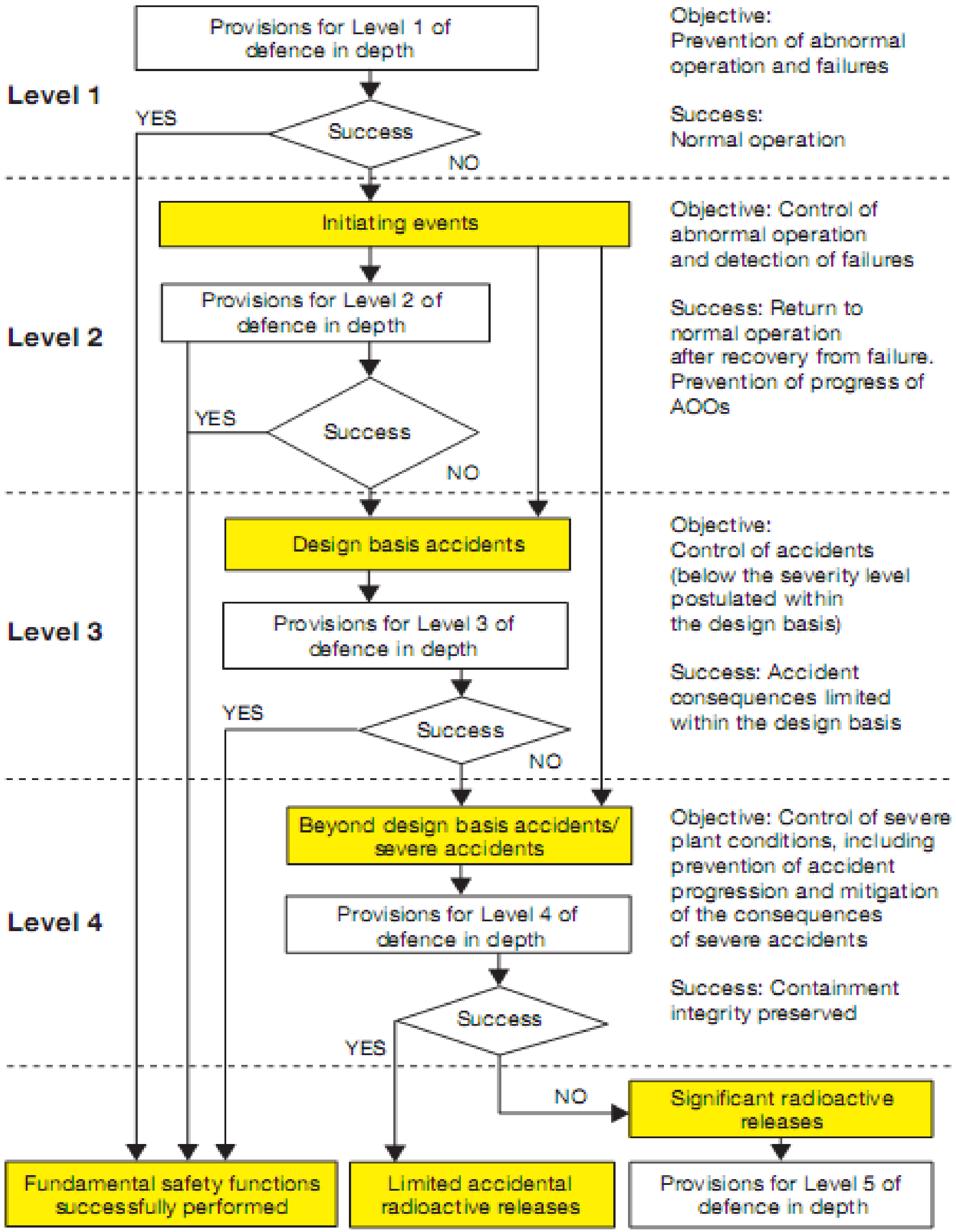


Approccio alla sicurezza nucleare

DIFESA IN PROFONDITA’

Barriere multiple inserite per evitare il rilascio della radioattività
- matrice del combustibile
- guaina del combustibile
- circuito primario
- sistema di contenimento

Safety Report Series No. 46, Assesment of defence in depth for nuclear power plants, N114, p. 6

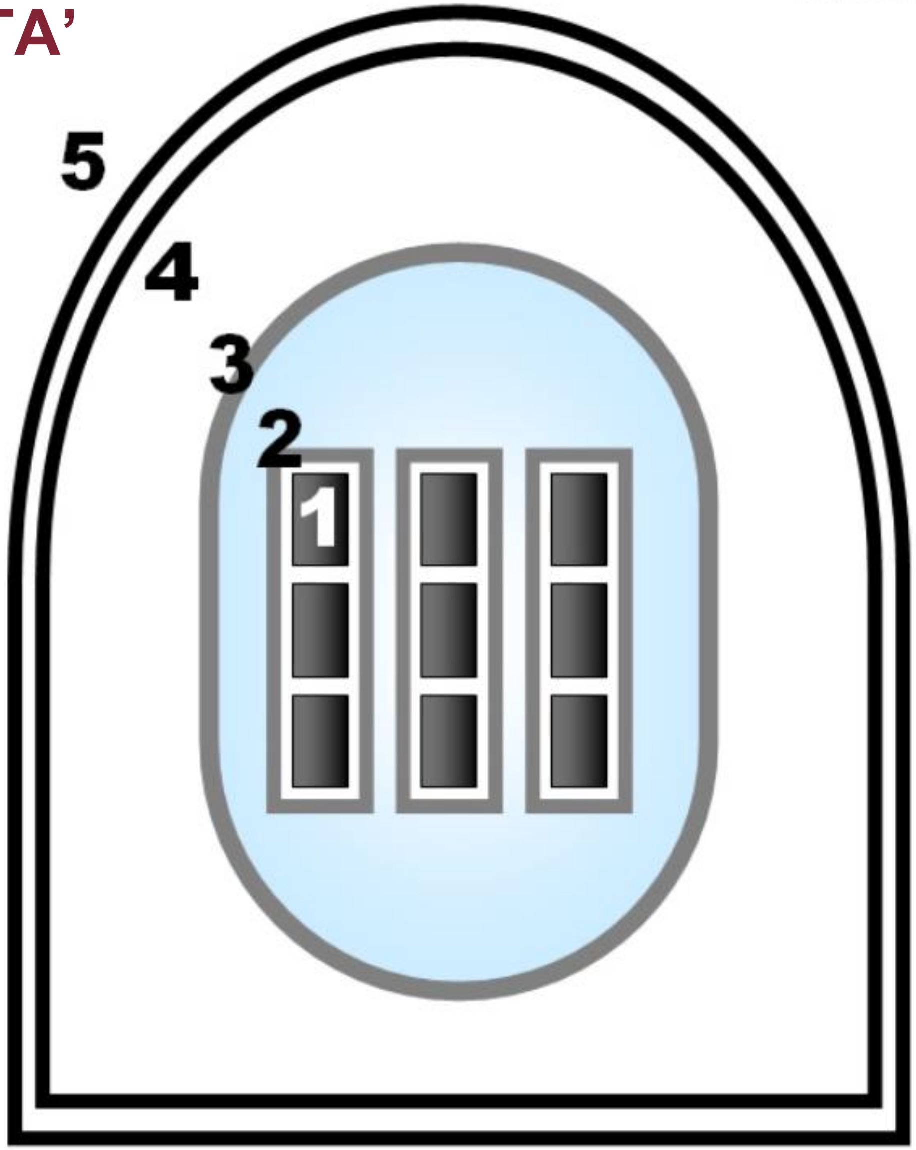


DIFESA IN PROFONDITA’

Levels of defence in depth	Objective	Essential means for achieving the objective
Level 1	Prevention of abnormal operation and failures	Conservative design and high quality in construction and operation
Level 2	Control of abnormal operation and detection of failures	Control, limiting and protection systems and other surveillance features
Level 3	Control of accidents within the design basis	Engineered safety features and accident procedures
Level 4	Control of severe plant conditions, including prevention of accident progression and mitigation of the consequences of severe accidents	Complementary measures and accident management
Level 5	Mitigation of radiological consequences of significant releases of radioactive materials	Off-site emergency response

DIFESA IN PROFONDITA'

Strategy	Accident prevention			Accident mitigation	
Operational state of the plant	Normal operation	Anticipated operational occurrences	Design basis and complex operating states	Severe accidents beyond the design basis	Post-severe accident situation
Level of defence in depth	Level 1	Level 2	Level 3	Level 4	Level 5
Objective	Prevention of abnormal operation and failure	Control of abnormal operation and detection of failures	Control of accidents below the severity level postulated in the design basis	Control of severe plant conditions, including prevention of accident progression, and mitigation of the consequences of severe accidents, including confinement protection	Mitigation of radiological consequences of significant releases of radioactive materials
Essential features	Conservative design and quality in construction and operation	Control, limiting and protection systems and other surveillance features	Engineered safety features and accident procedures	Complementary measures and accident management, including confinement prodection	Off-site emergency response
Control	Normal operating activities		Control of accidents in design basis	Accident management	
Procedures	Normal operating procedures		Emergency operating procedures	Ultimate part of emergency operating procedures	
Response	Normal operating systems		Engineered safety features	Special design features	Off-site emergency preparations
Condition of barriers	Area of specified acceptable fuel design limit		Fuel failure; Severe fuel damage	Fuel melt; Uncontrolled fuel melt	Loss of confinement
Colour code	NORMAL		POSTULATED ACCIDENTS		EMERGENCY



Analisi di tipo probabilistico e deterministico combinate per garantire elevata sicurezza

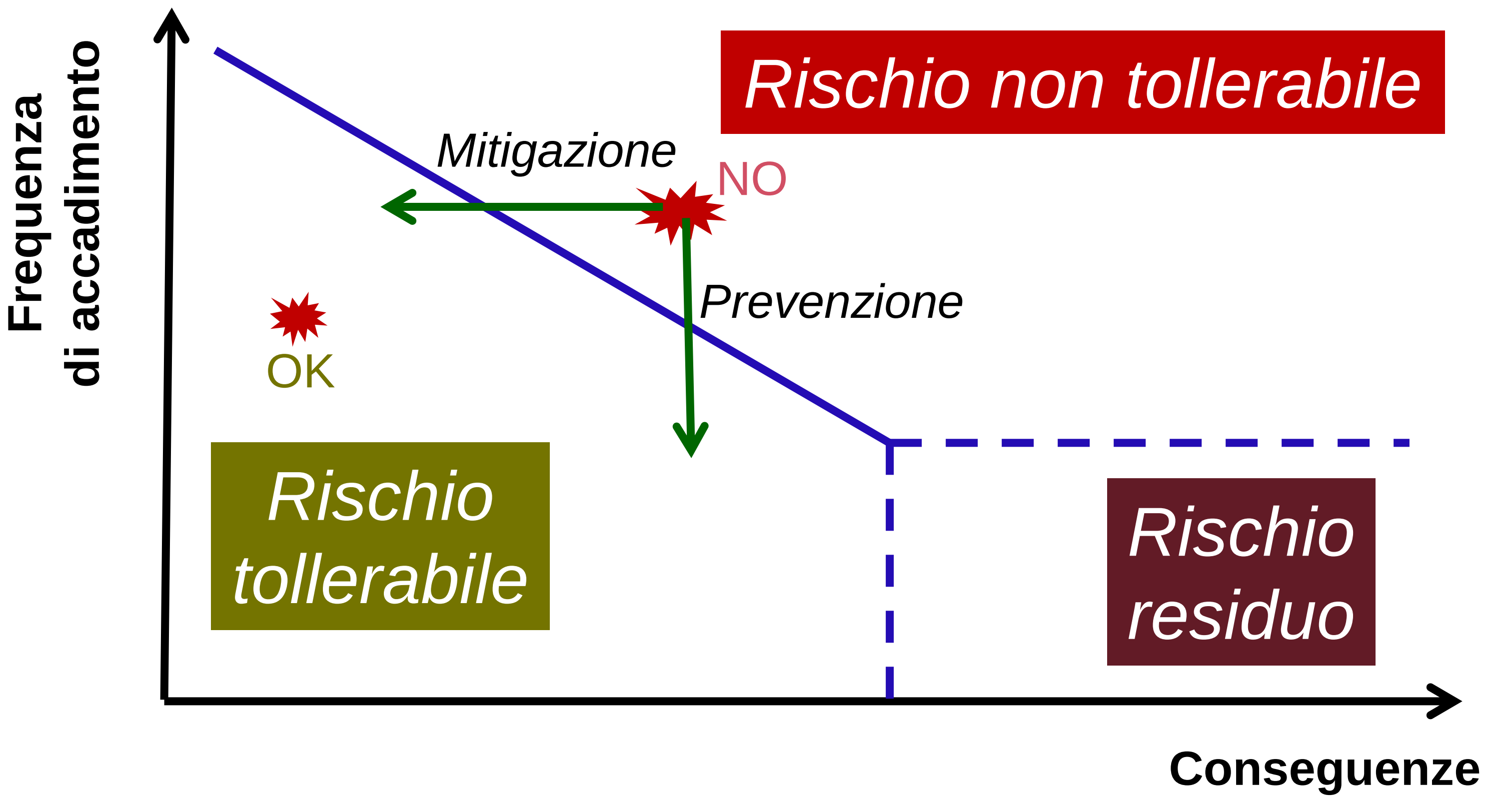
Le analisi probabilistiche

- Individuano tutti i possibili moti di guasto
- Valutano le probabilità di accadimento

Le analisi deterministiche

- Valutano l'adeguatezza dei sistemi di sicurezza
- Calcolano le possibili conseguenze

Valutazione del rischio

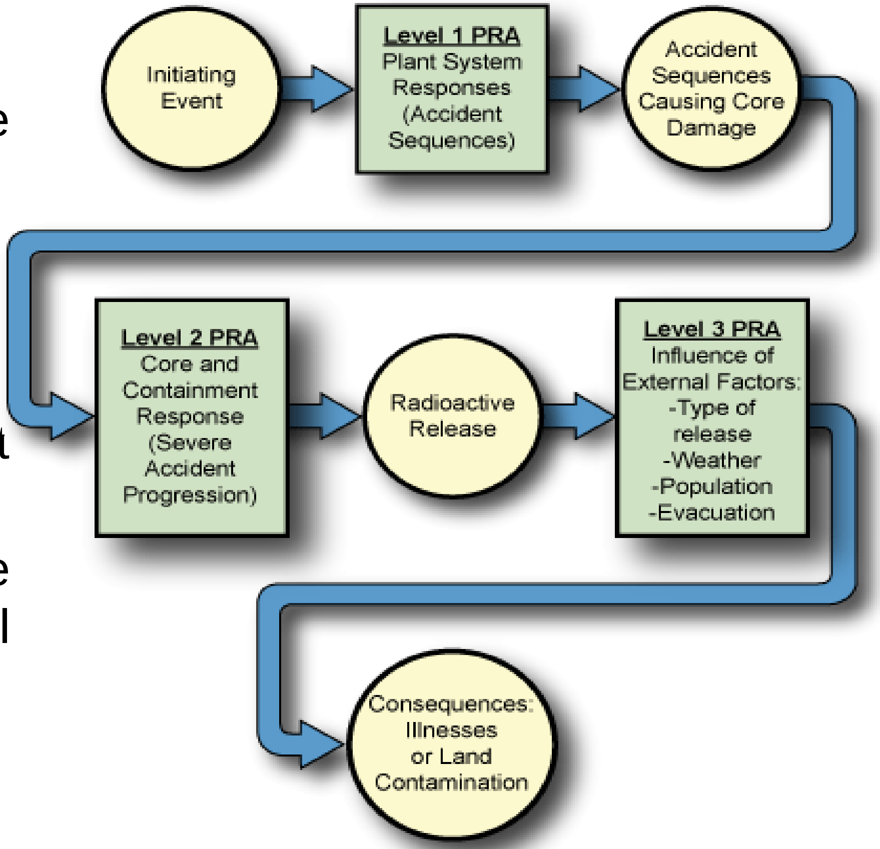


Curva di Farmer

Combined probabilistic and deterministic safety analysis

Into the nuclear power plants safety, three levels of PSA/DSA are defined:

- Level 1: The assessment of core damage frequency.
- Level 2: The assessment of containment release frequency.
- Level 3: The assessment of off-site consequences (public and environmental risk)



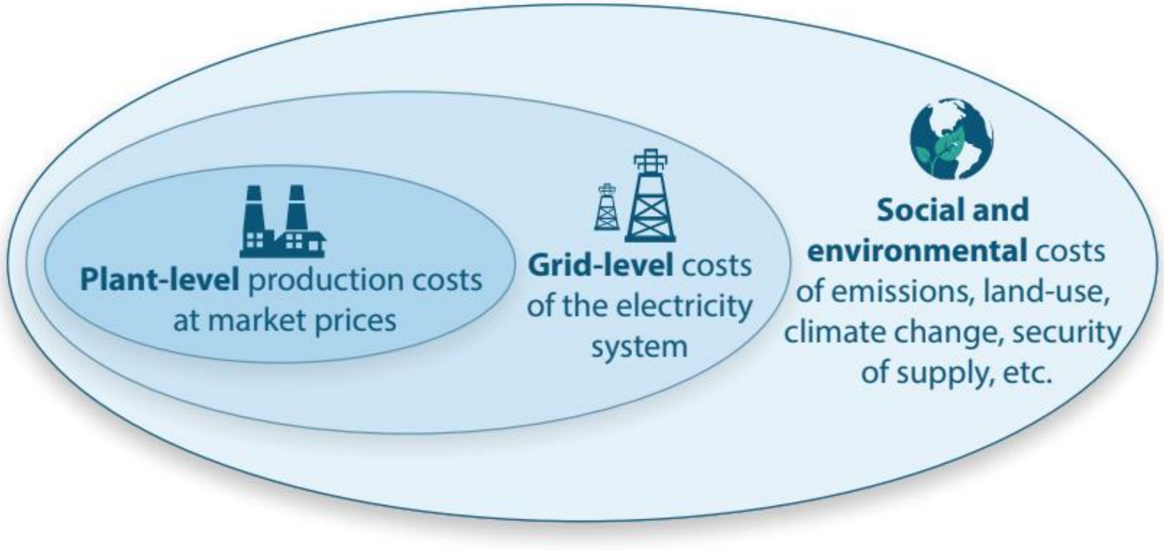
Morti per TWh, Conservative assumpitions

- **Chernobyl accident**, there are several death estimates. 4000 possible past or future fatalities by the World Health Organization (WHO) – the most-widely cited figure – although this is considered to be too high by several researchers, including a later report by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR)*.
- The **Fukushima accident.** No one died directly from the Fukushima disaster. According to Japanese authorities 573 people died due to the impact of the evacuation and stress and 1 from cancer with possible relation with the dose received.
- Markandya and Wilkinson (2007) estimated for occupational deaths, most from milling and mining. Their published rate is 0.022 deaths per TWh.

- The sum of these three data points gives us a death rate of 0.07 deaths per TWh

is 9 mSv).

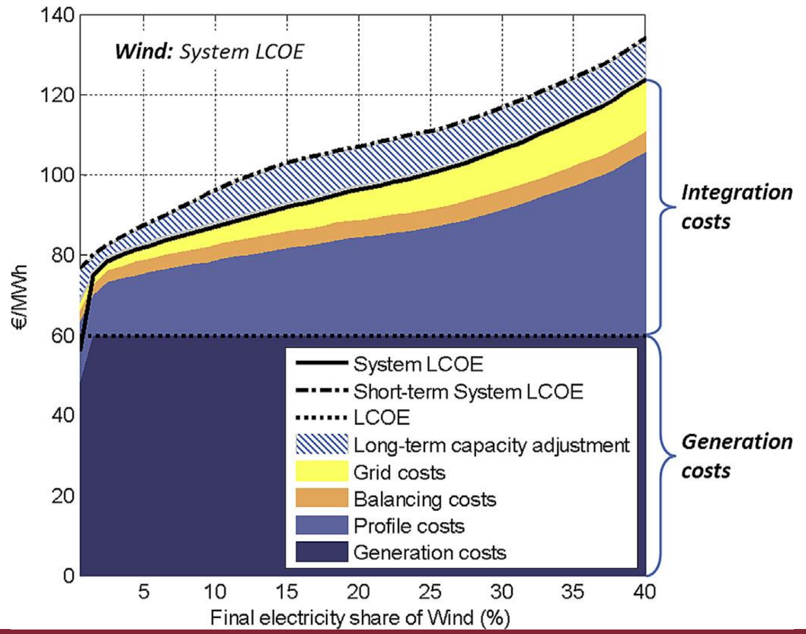
Cost Comparison with Other Energy Sources



Source: Adapted from NEA (2012).

Total economic system costs, then, are defined as **plant-level generating costs** plus **grid-level system costs**. Taking this systems level perspective includes:

- **Profile and balancing costs** – the grid-level costs imposed by variability and uncertainty.
- **Connection, distribution, and transmission costs** – the costs of delivering electricity from distributed power generation to customers.



IPOTESI 2050 TERNA

	PNIEC	SCENARIO CON NUCLEARE	SCENARIO SENZA NUCLEARE
Totale FRNP (GW)	**296**	**246**	**270**
di cui solare	245	180	200
di cui eolico onshore	36	46	50
di cui eolico offshore	15	20	20
Totale accumuli (GWh)	**n/a**	**196**	**216**

BILANCIO ELETTRICO (TWh_el)	SCENARIO CON NUCLEARE	SCENARIO SENZA NUCLEARE
Fabbisogno elettrico totale	583	
Totale produzione nazionale	546	540
Solare, eolico e idrico[51]	435	474
Nucleare	69	-
Altra produzione programmabile	42	66
Saldo estero (import netto)	48	57
Perdite accumuli	-11	-14
Copertura zero-emissioni (rinnovabile e nucleare) (%)	89%	84%
Overgeneration (% su fabbisogno)	4,8%	4,4%

Initiating events for DEC-B

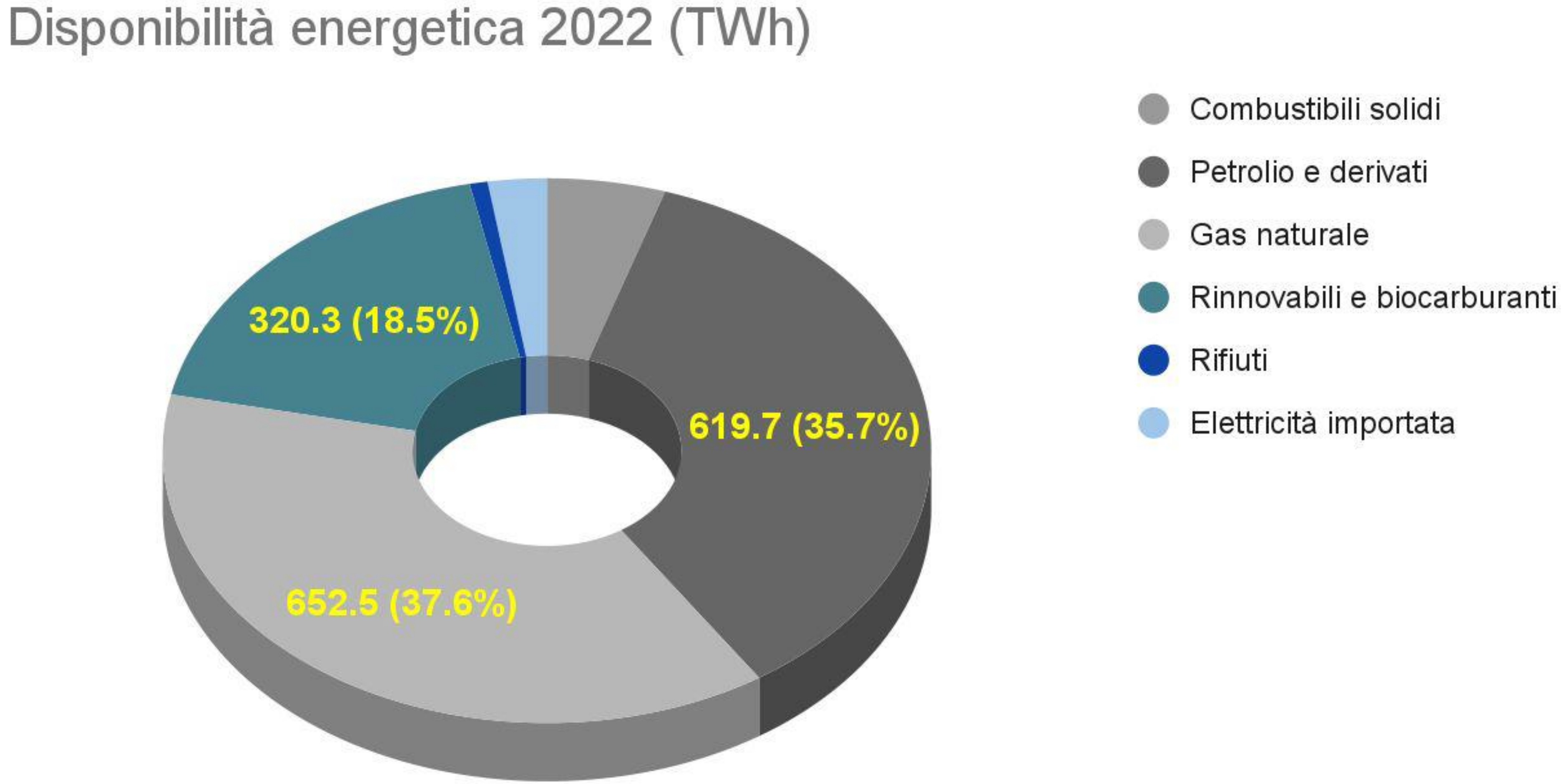
- **The set of category DEC B events shall be postulated and justified to cover situations, where the capability of the plant to prevent severe fuel damage is exceeded or where measures provided are assumed not to function as intended, leading to severe fuel damage.**

- For DEC B (severe accidents) an approach different from that for the selection of DEC A has to be taken, since there will usually be a very large number of possible scenarios, based on a wide range of plant specific severe accident conditions and phenomena, which cannot all be captured at the start of a selection process. Accordingly, no list of initiating events is provided for DEC B.

- A set of severe fuel damage scenarios has to be identified for analysis, covering the different situations and conditions which can occur at the outset and during the course of a severe accident.
- The selection process of representative scenarios should notably make use of the PSA results, the overall understanding of the physical phenomena involved, the margins in the design and the systems' redundancy and diversity. As far as necessary, preliminary analyses of scenarios should be performed as part of the selection process.

- **IN CASE OF FLR, partial fuel damage…**

La dimensione del problema..



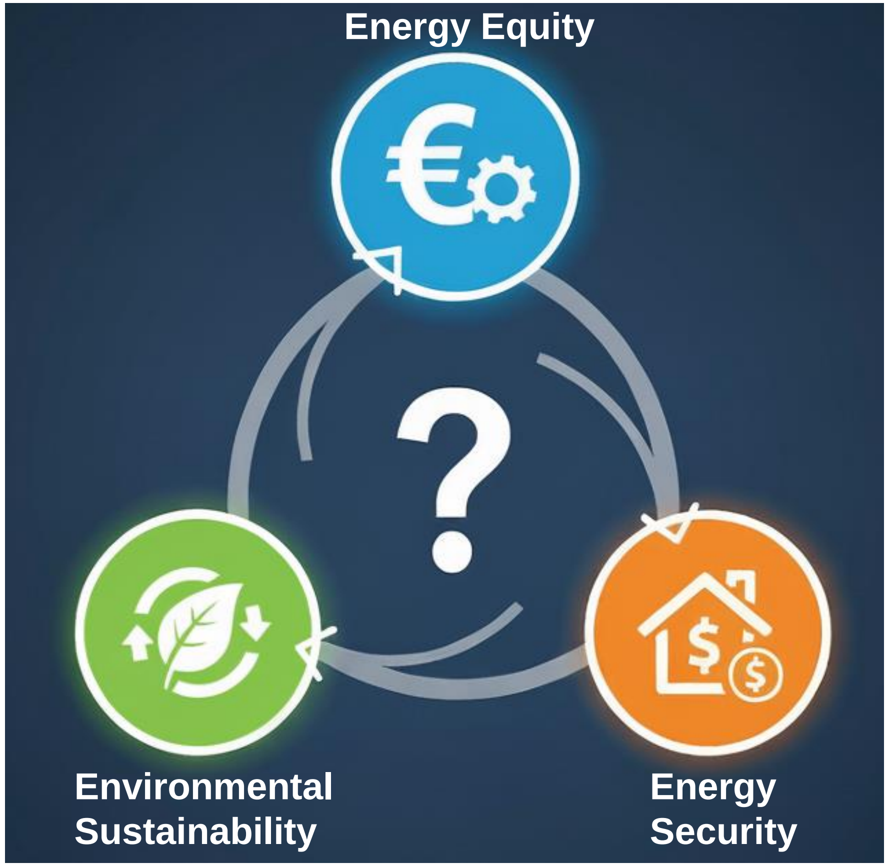
Source: “LA SITUAZIONE ENERGETICA NAZIONALE NEL 2022”, Rapporto MASE, luglio 2023

Trilemma energetico

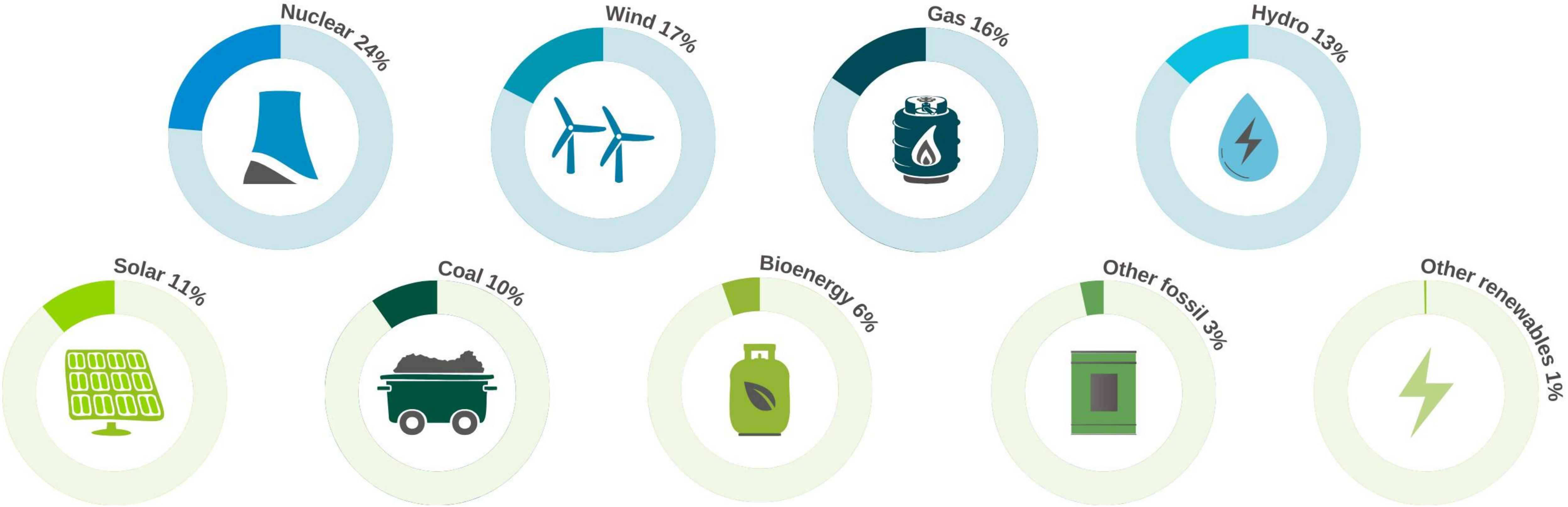
Il **Trilemma Energetico** descrive la complessa sfida di bilanciare tre obiettivi fondamentali, spesso contrastanti, per un sistema energetico sostenibile ed efficiente.

- **Sicurezza Energetica (Energy Security)**
  - Garantire l'affidabilità delle forniture energetiche.
  - Gestire la dipendenza dalle importazioni e i rischi geopolitici.
  - Assicurare la resilienza delle infrastrutture.
- **Equità Energetica (Energy Equity)**
  - Assicurare l'accesso all'energia per tutti.
  - Mantenere l'energia economicamente accessibile (conveniente) per famiglie e imprese.
- **Sostenibilità Ambientale (Environmental Sustainability)**
  - Ridurre le emissioni di gas serra e l'impatto climatico (decarbonizzazione).
  - Minimizzare l'inquinamento e l'impatto sugli ecosistemi.
  - Gestire l'uso delle risorse (acqua, suolo, materiali critici).

Migliorare una dimensione può compromettere temporaneamente le altre. La vera sfida è trovare un equilibrio ottimale tra i tre vertici.



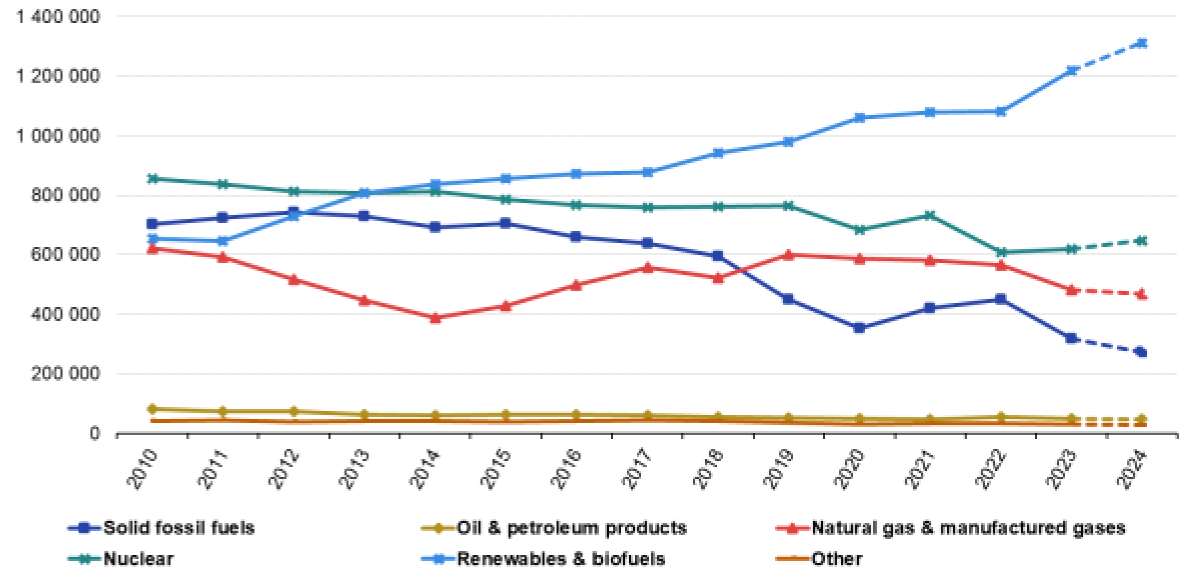
Electricity generation by technology in EU (% in 2024)



Source: EMBER

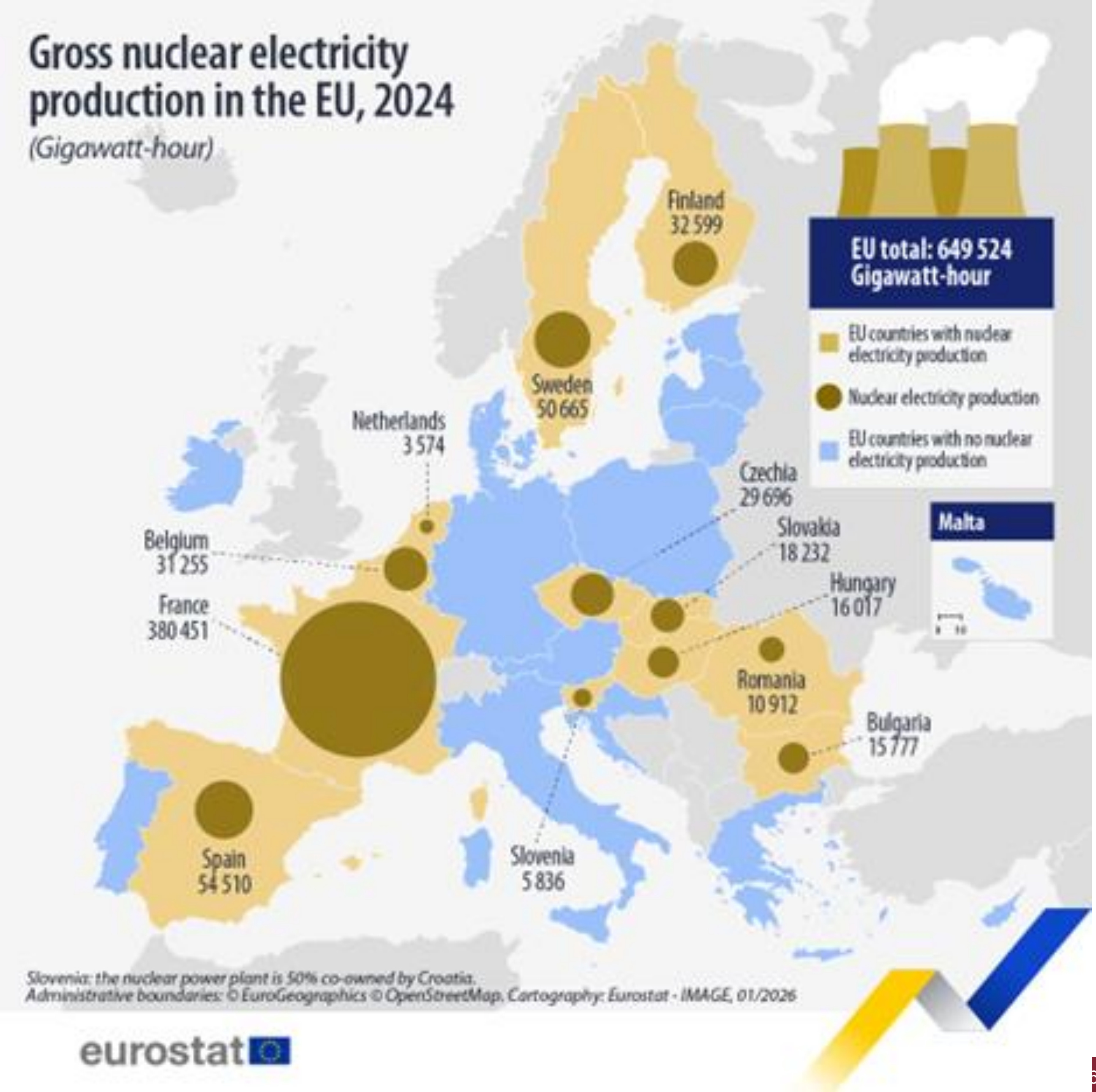
Current Status

Gross electricity production by fuel group, EU, 2010-2024
(GWh)



note: 2024 data preliminary
Source: Eurostat online data codes: nrg_ind_pehcf, nrg_ind_pehnf)

eurostat

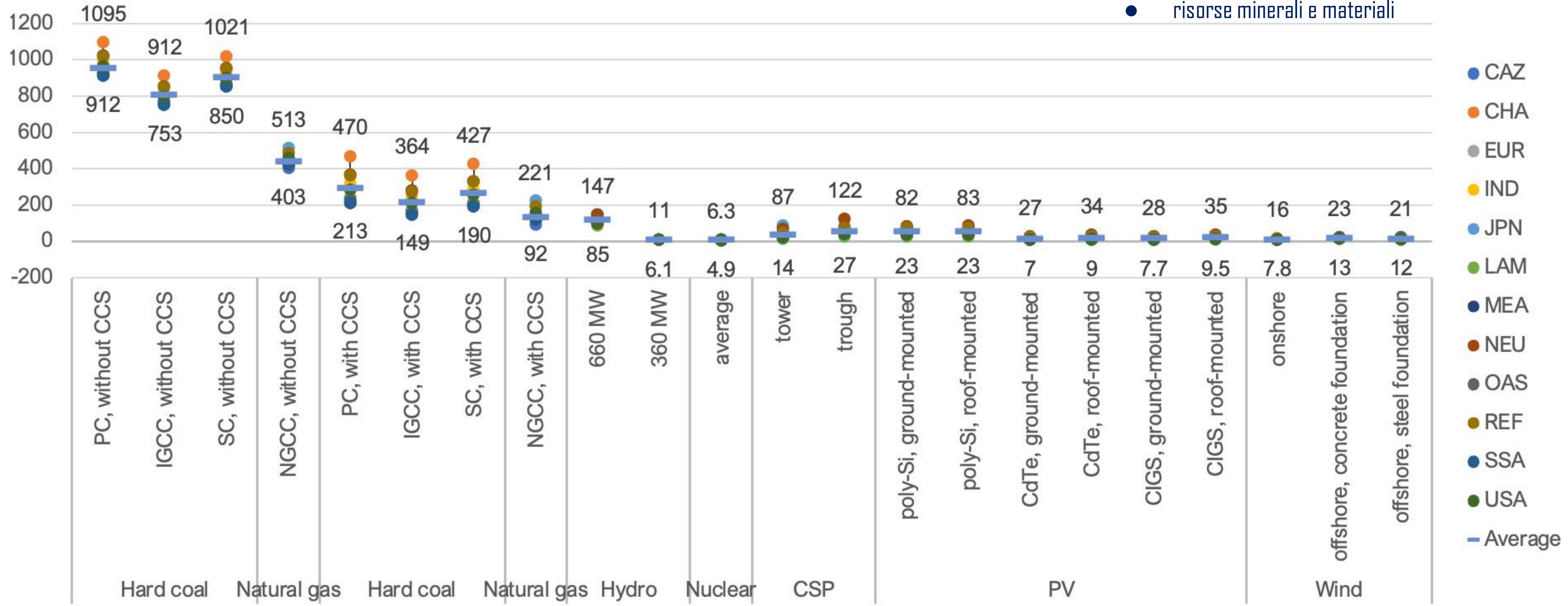


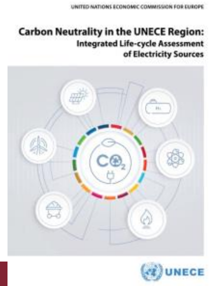
Sostenibilità ambientale

Environmental Impact

- emissioni di gas serra (GHG)
- radiazioni ionizzanti
- tossicità verso l'ecosistema
- occupazione di suolo
- uso di acqua
- risorse minerali e materiali

Lifecycle GHG emissions, in g CO_2 eq. per kWh, regional variation, 2020





Source: Life Cycle Assessment of Electricity Generation Options | UNECE. unece.org. Retrieved Feb. 26, 2022

Environmental Impact

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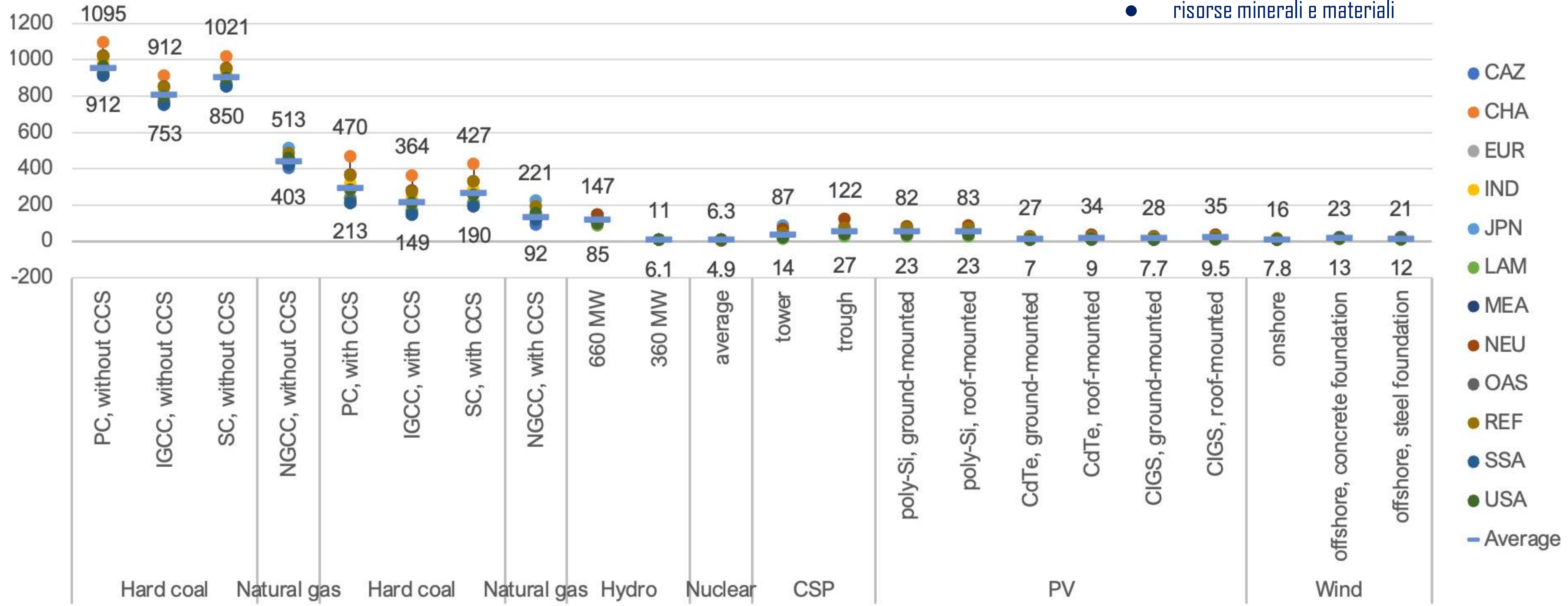
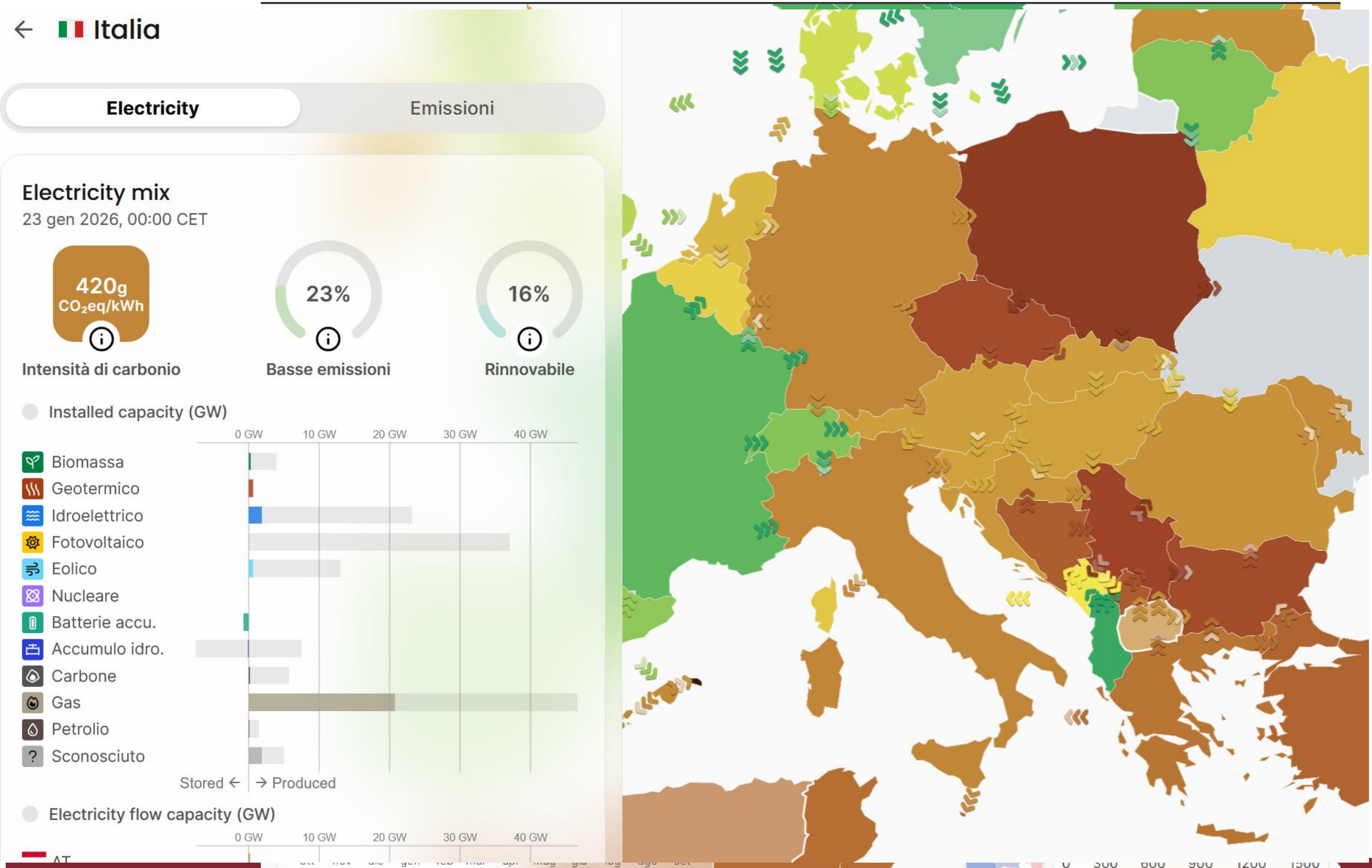
Lifecycle GHG emissions, in g CO_2 eq. per kWh, regional variation, 2020



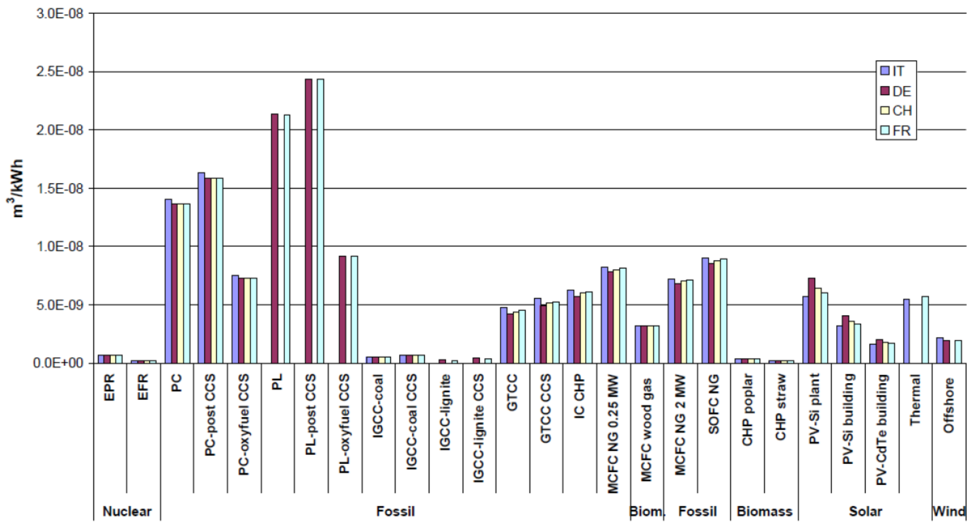
Source: Life Cycle Assessment of Electricity Generation Options | UNECE. unece.org. Retrieved Feb. 26, 2022



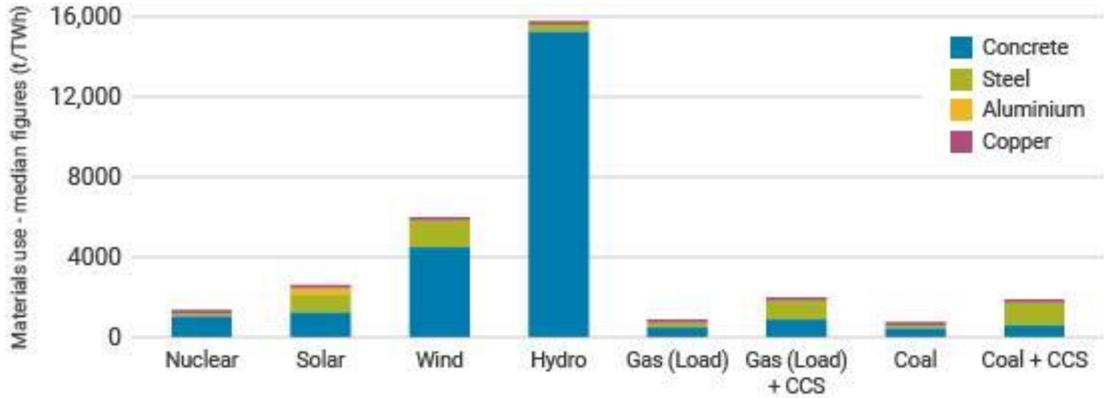
Italia
Electricity
Emissioni
Electricity mix
23 gen 2026, 00:00 CET
420g CO₂eq/kWh
Intensità di carbonio
23%
Basse emissioni
16%
Rinnovabile
Installed capacity (GW)
0 GW
10 GW
20 GW
30 GW
40 GW
Biomassa
Geotermico
Idroelettrico
Fotovoltaico
Eolico
Nucleare
Batterie accu.
Accumulo idro.
Carbone
Gas
Petrolio
Sconosciuto
Stored
Produced
Electricity flow capacity (GW)
AT

Environmental Impact

Figure 3.2-16. Chemical waste volumes from different electricity generation technologies[43]



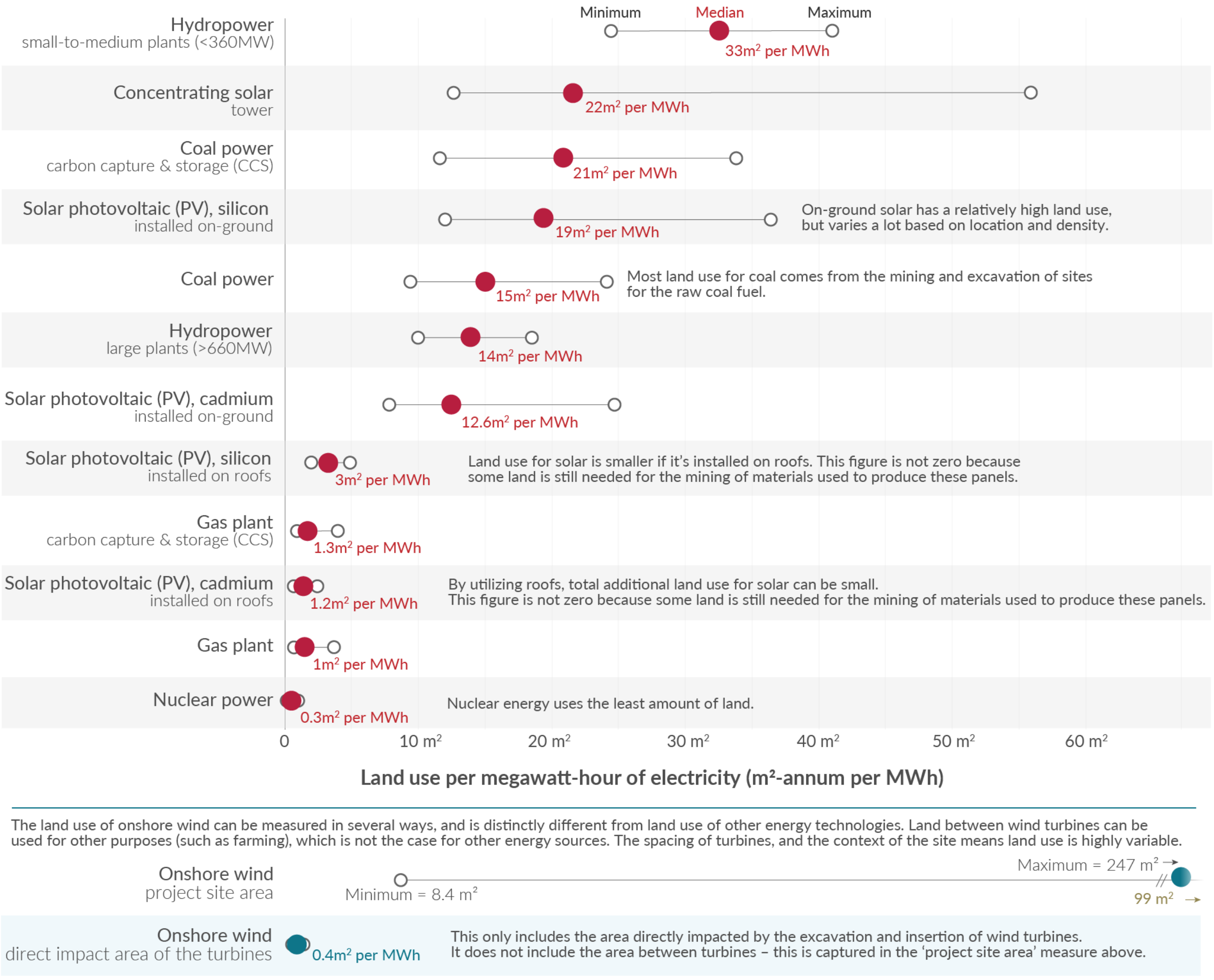
Source: [3.2-10]



Land use of energy sources per unit of electricity

Our World in Data

Land use is based on life-cycle assessment; this means it does not only account for the land of the energy plant itself but also land used for the mining of materials used for its construction, fuel inputs, decommissioning, and the handling of waste.

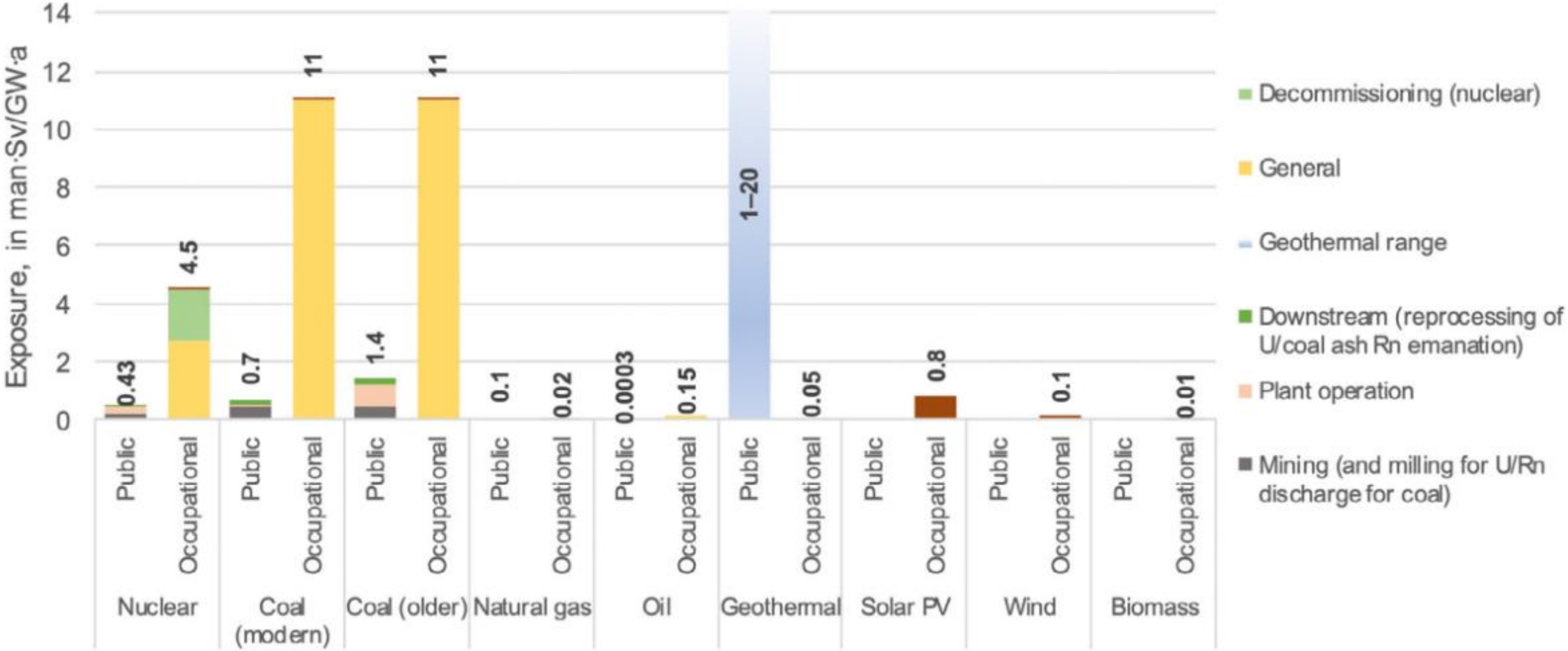


Note Capacity factors are taken into account for each technology which adjusts for intermittency. Land use of energy storage is not included since the quantity of storage depends on the composition of the electricity mix.

Source: UNECE (2021). Lifecycle Assessment of Electricity Generation Options. *United Nations Economic Commission for Europe* for all data except wind. Wind land use calculated by the author.

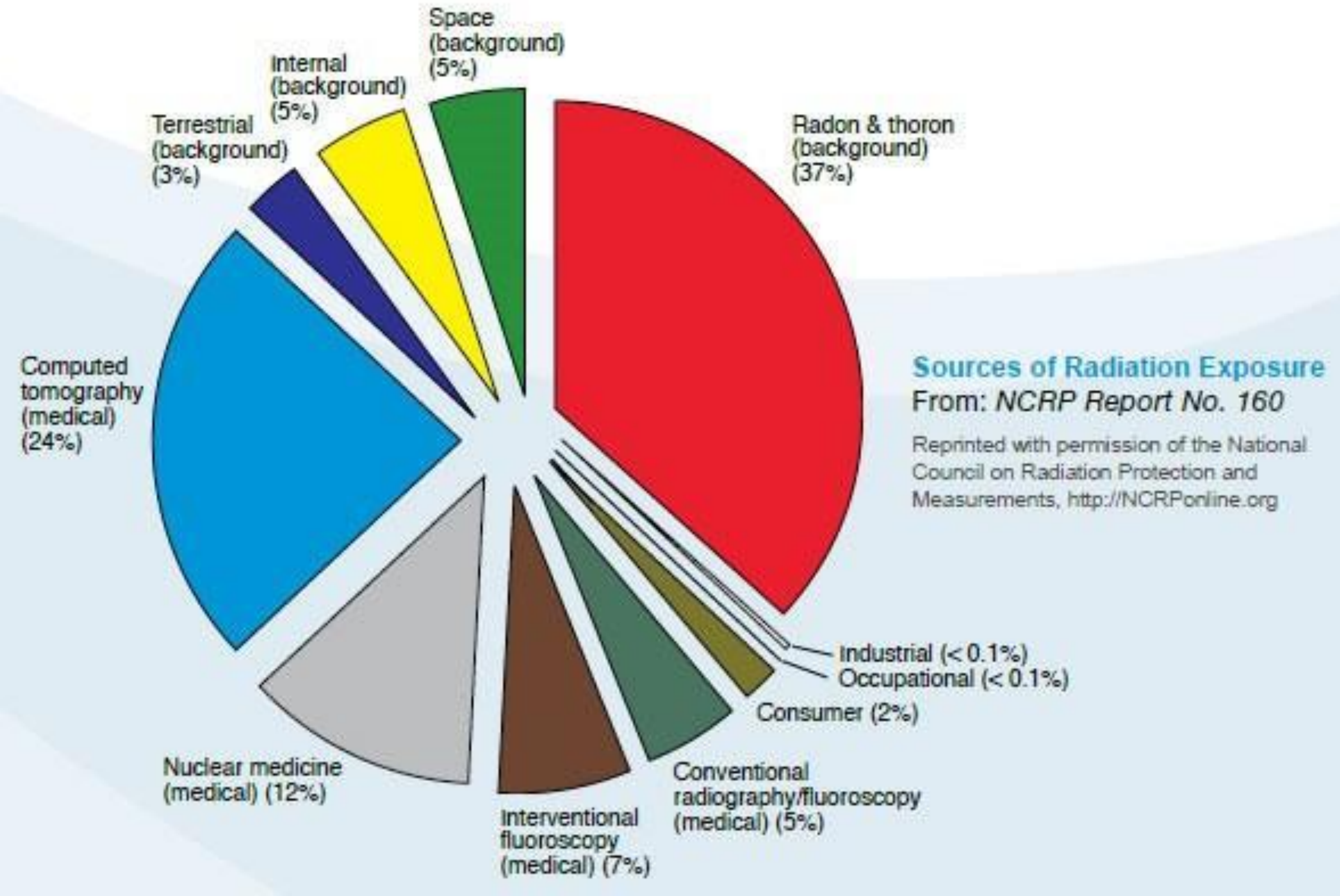
See OurWorldinData.org/land-use-per-energy-source for more research on this topic.

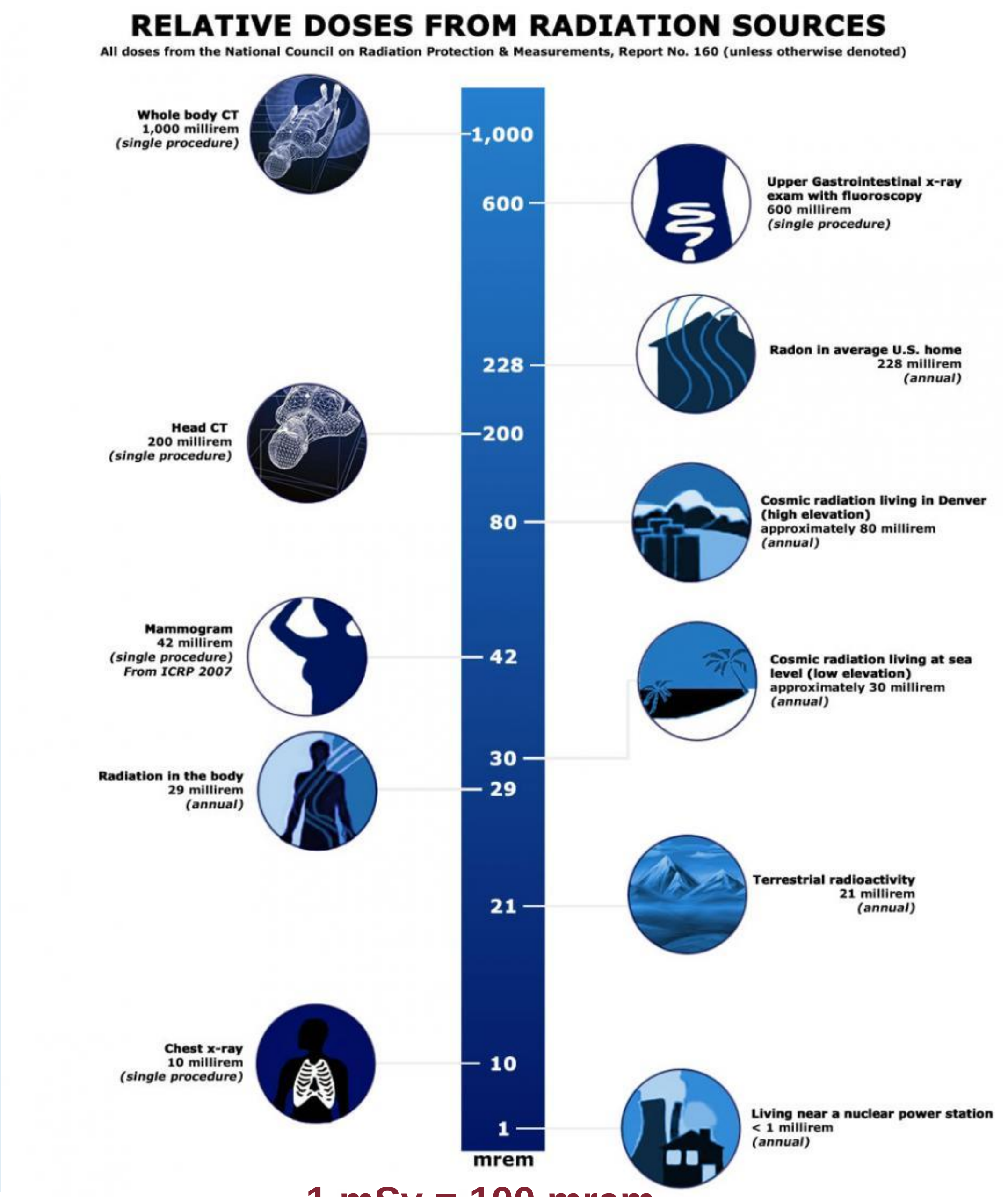
Environmental Impact



Esposizione a radiazioni ionizzanti valutata per il ciclo di vita di diverse tecnologie di generazione elettrica [Fonte: "UNSCEAR 2016 - ANNEX B - RADIATION EXPOSURES FROM ELECTRICITY GENERATION].

Human radiation exposure by source





1 mSv = 100 mrem

"Materiali Critici" per generare 1 TWh di Energia "Stabile"

ùMentre per la realizzazione di centrali nucleari si usano quasi solo materiali comuni (Acciaio/Cemento) e la supply chain è per più del 90% EU, il sistema Solare+Batterie dipende da una catena di approvvigionamento complessa e costosa, quasi interamente extra-EU.

- **Rame:**
  - **Nucleare:** ~1-2 t/TWh (Cablaggio interno minimo).
  - **Solare+Storage:** ~150 t/TWh. Ogni pannello, inverter e cella della batteria richiede rame.
- **Litio, Nichel, Cobalto (Il "serbatoio"):**
  - **Nucleare: 0 t/TWh**.
  - **Solare+Storage: ~200+ t/TWh**. Questi materiali servono *solo* per immagazzinare l'energia, non per produrla.

La transizione verso le rinnovabili sposta la dipendenza dai combustibili fossili (consumo continuo di gas/carbone) alla dipendenza dai minerali critici (consumo intensivo di metalli rari in fase di costruzione).

Grazie all'altissima densità energetica, le centrali nucleari sono l'unica tecnologia low-carbon che minimizza drasticamente l'uso di risorse minerarie e suolo.

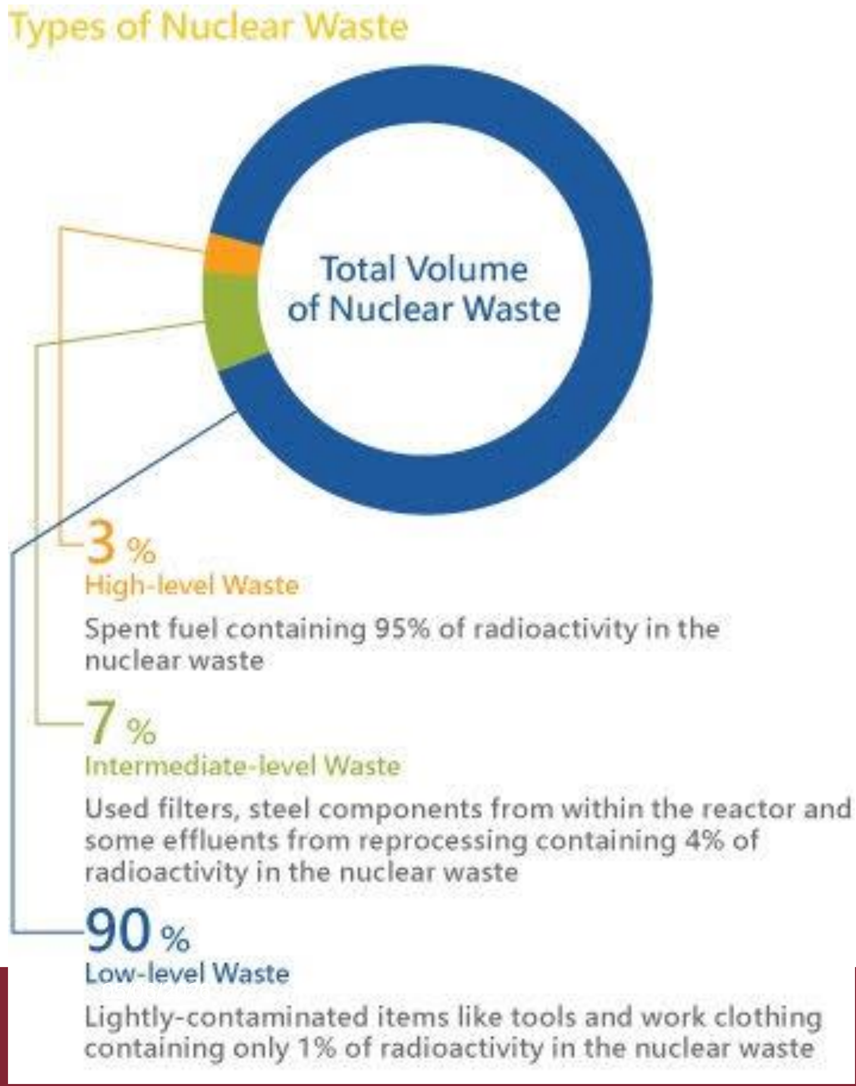
Materiali Richiesti per Energia Prodotta (Tonnellate/TWh prodotto)

Material	Nuclear	Solar PV (Utility)	Wind (Onshore)	Wind (Offshore)	Hydro	Coal	Gas (CCGT)
Concrete	1,060	1,220	4,470	~1,500*	15,320	870	400
Steel	130	940	1,450	1,900	330	310	170
Copper	2.5	68	39	90	5	1	1
Aluminum	0.3	35	17	10	9	3	1
Glass	< 1	1,600**	92	< 1	< 1	< 1	< 1
Silicon	0	~7***	0	0	0	0	0
Total Critical Minerals†	**~5**	**~124**	**~130**	**~200**	**~15**	**~7**	**~8**

Fonti: Agenzia Internazionale dell'Energia (IEA, "The Role of Critical Minerals in Clean Energy Transitions"), e Joint Research Centre (JRC) della Commissione Europea.

Nuclear Waste Management

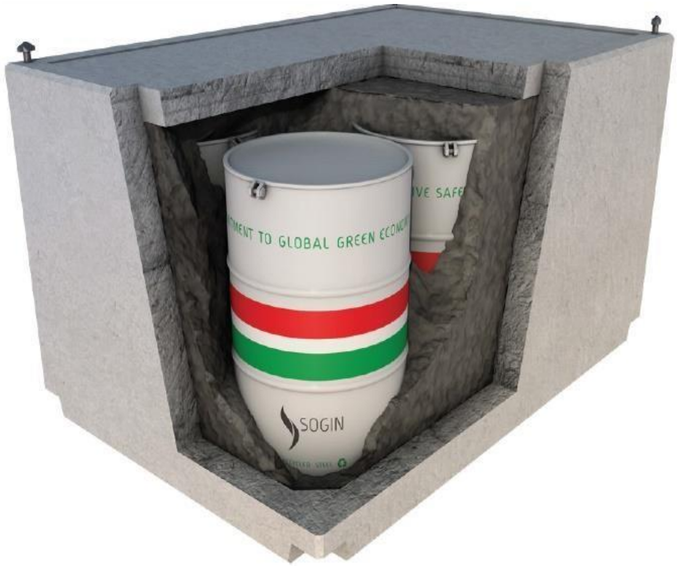
- Types of Nuclear Waste
  - Low, intermediate, and high-level waste.
- Current and Future Waste Disposal Methods
  - Low and intermediater waste: superficial or near



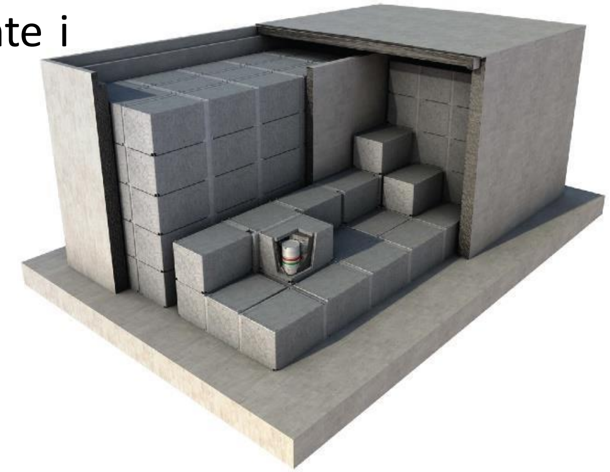
- Council Directive 2011/70/EURATOM of 19 July 2011 establishing a Community framework for the responsible and safe management of spent fuel and radioactive waste

Deposito nazionale: Le barriere ingegneristiche

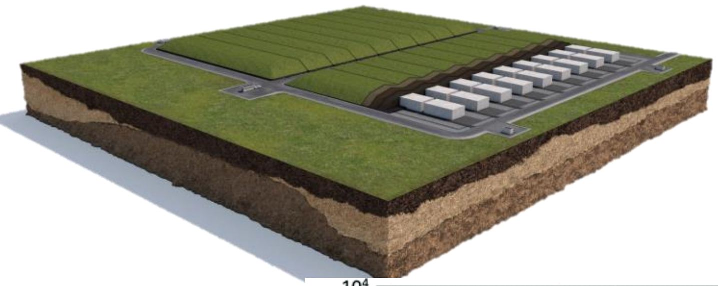
- Prima barriera:
  i manufatti, costituite da contenitori metallici e dai rifiuti radioattivi al loro interno, già condizionati in una forma solida
- Seconda barriera:
  I moduli, strutture a forma di parallelepipedo (3 m x 2 m x 1,7 m) in calcestruzzo speciale, armato o fibrorinforzato, assicurano la loro resistenza per oltre 300 anni.

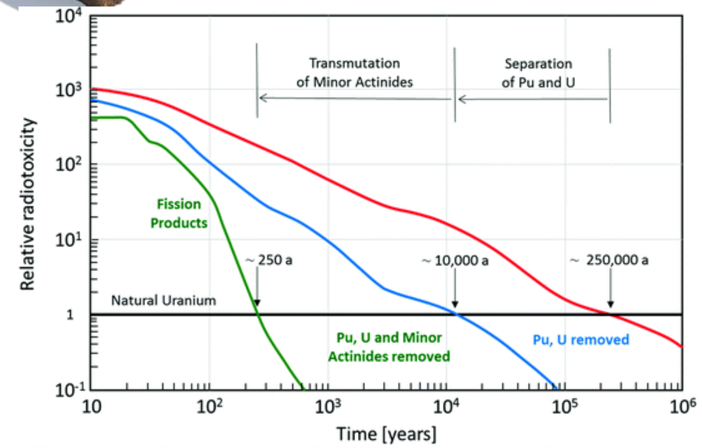


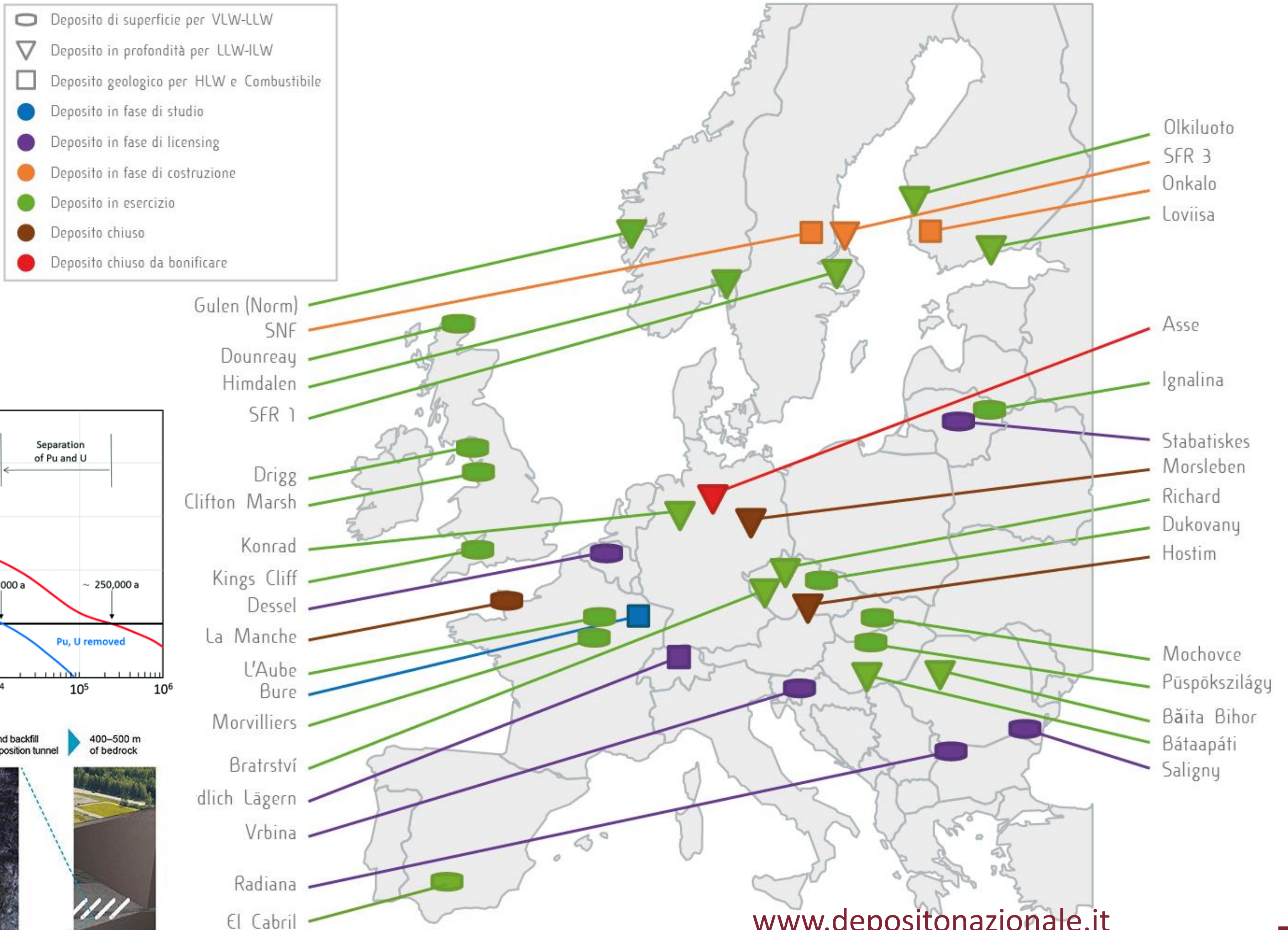
- Terza barriera:
  Le celle sono gli edifici in calcestruzzo armato speciale (27m x 15,5 m x 10 m), progettate per resistere per almeno 300 anni, dove verranno sistemati definitivamente i rifiuti radioattivi.
- Quarta barriera:
  la copertura multistrato è una struttura artificiale disposta a copertura delle celle. Viene realizzata con strati di diversi materiali, per uno spessore complessivo di qualche metro, per impedire l'ingresso di acqua nel deposito, drenare le acque piovane, isolare i rifiuti dall'ambiente.



Nuclear Waste Management







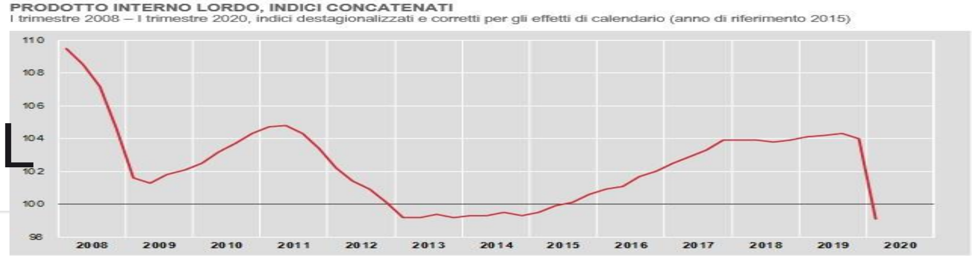
www.depositonazionale.it

Sicurezza Energetica

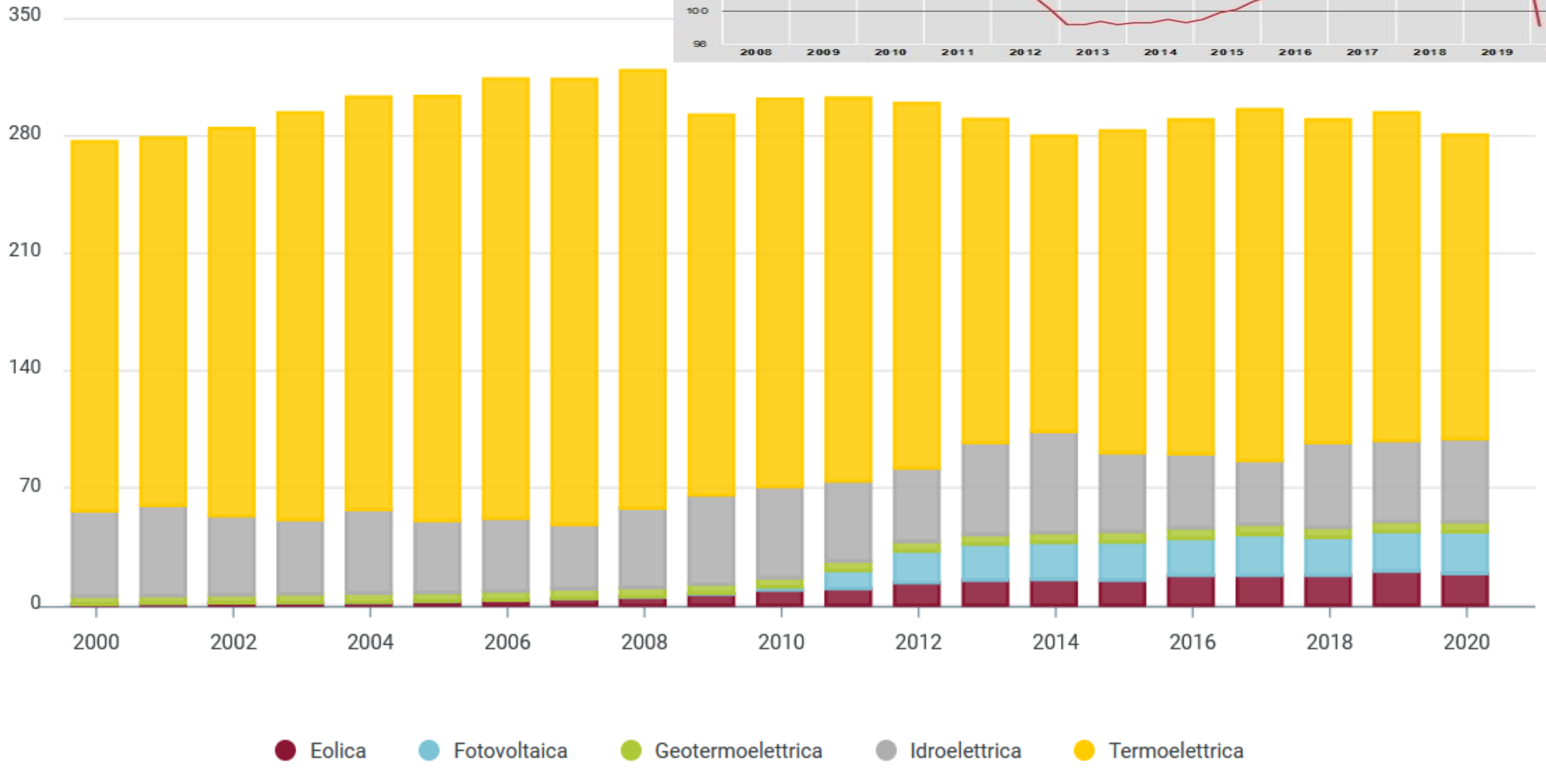
Produzione di energia elettrica per fonte in Italia

Source: https://www.terna.it/it/sistema-elettrico/statistiche/evoluzione-mercato-elettrico

Source: ISTAT



… legame con il PIL



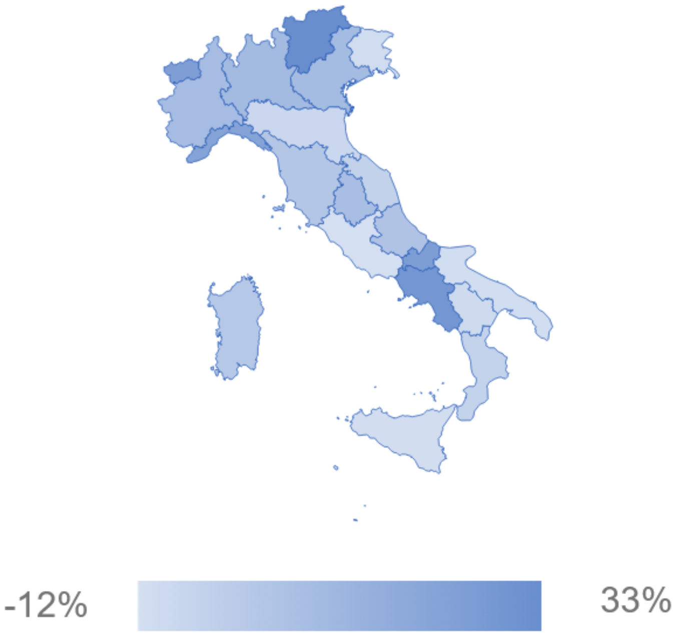
Anno: 2024 | Regione: All | Produzione: Lorda | Fonte: All

Produzione di energia totale

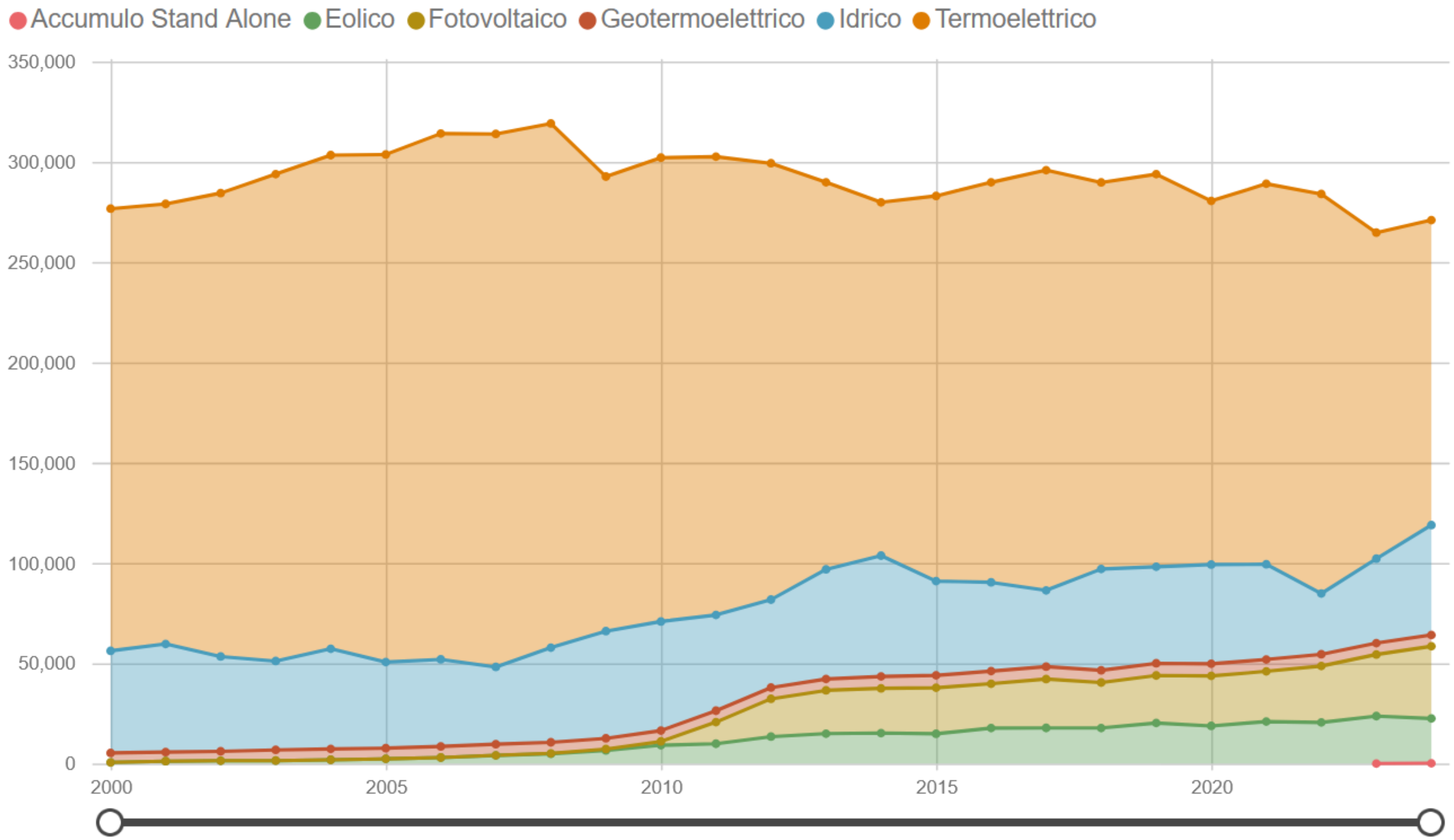
270,963.09 GWh

⤴ 2.4% (YoY% - 2024)

Produzione YoY% nelle regioni



Produzione per fonte [GWh]

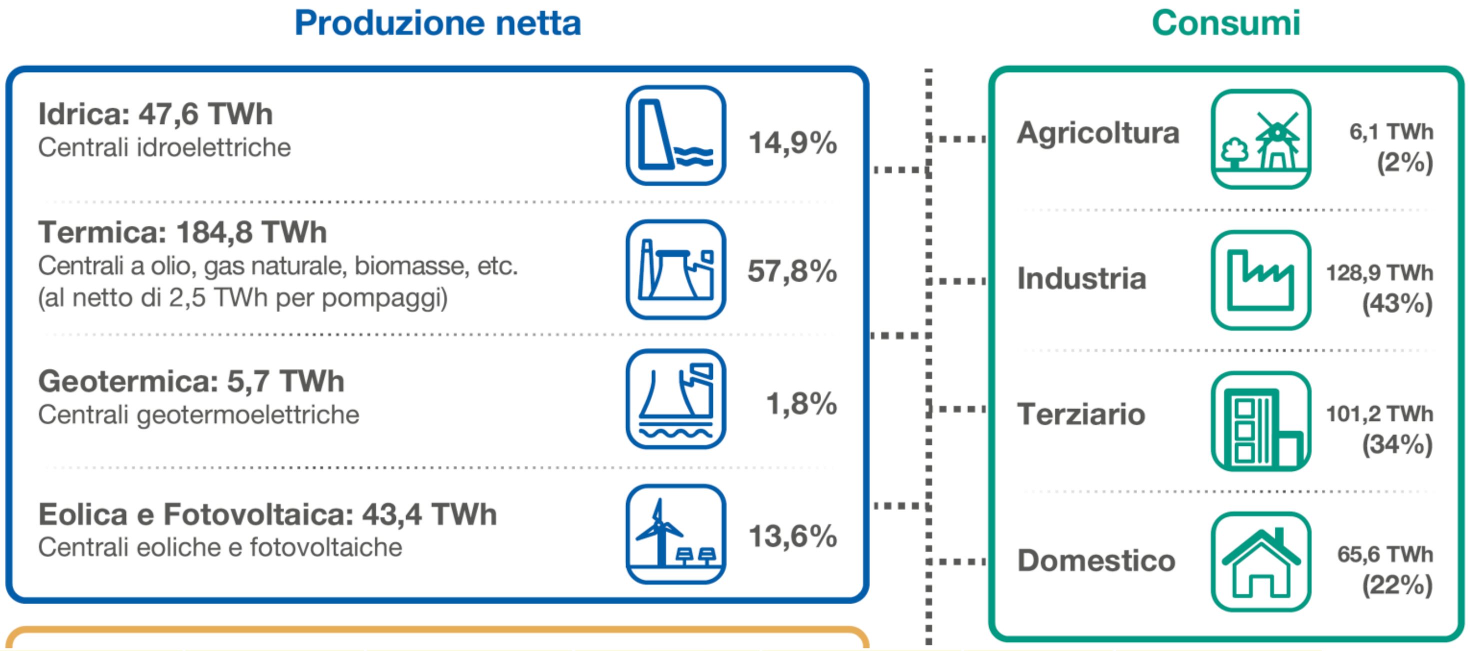


Produzione per fonte

Eolico	Fotovoltaico	Geotermoelettrico	Idrico	Termoelettrico	Accumulo Stand Alone
(8.2%)	(13.3%)	(2.1%)	(20.2%)	(56.1%)	(0.1%)
22,321.89 GWh	35,993.10 GWh	5,674.97 GWh	54,756.96 GWh	152,080.22 GWh	135.94 GWh
⤵ -5.6%	⤴ 17.2%	⤵ -0.4%	⤴ 30.2%	⤵ -6.5%	⤴ 1526.3%

Bilancio elettrico 2019 italiano

Source: TERNA



MWh	Francia	Svizzera	Austria	Slovenia	Altri	Totale
IMPORT	**15.244**	**22.194**	**1.229**	**5.193**	**115**	**43.975**
EXPORT	948	981	2	245	3.658	5.834

In continua crescita. Ora (2025) supera i 50 TWh

DOMANDA: 319,6 TWh

Consumi di energia elettrica in Italia

2025

Terna Driving Energy

311,3 mld kWh nel 2025 → **-0,2%** SUL 2024

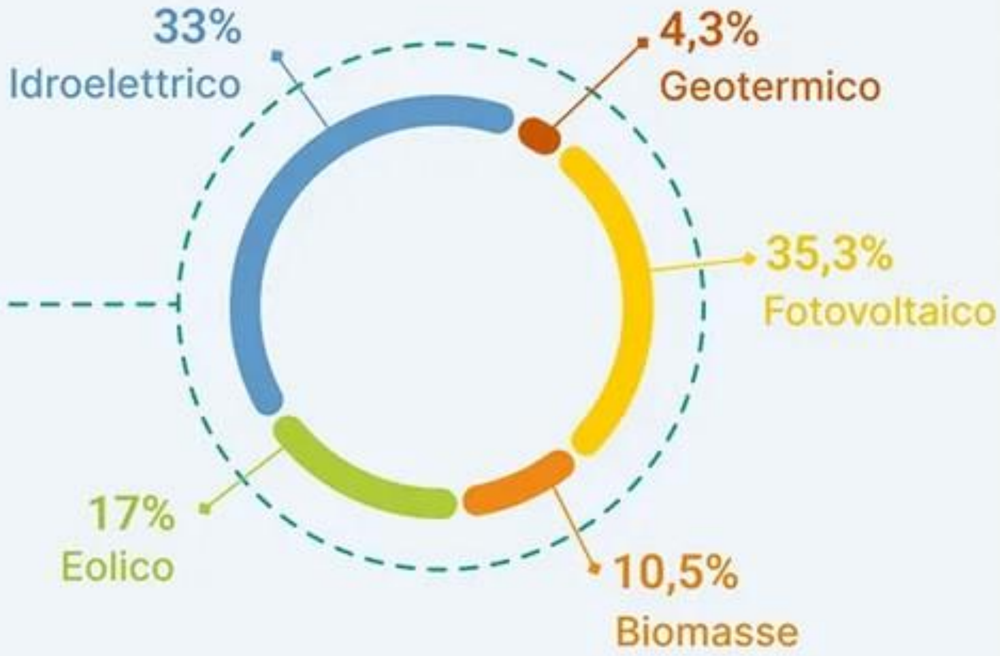
Consumi industriali*

-0,7% SUL 2024

*Indice IMCEI

84,9% Produzione nazionale

15,1% Energia scambiata con l'estero



Terna Driving Energy | Dati

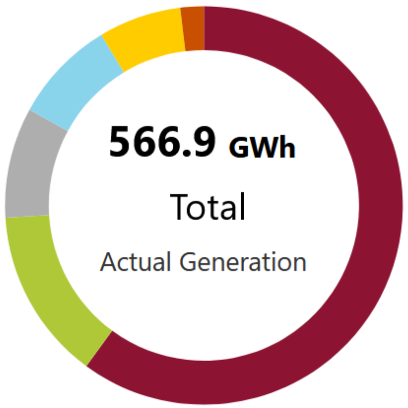
Fabbisogno | Generazione | Trasmissione | Mercato e Adeguatezza | Connessioni | Corr
Download Center

Today | Last 30 days | Last 365 days | Custom range | 24/01/2026 | 24/01/2026

Actual Generation

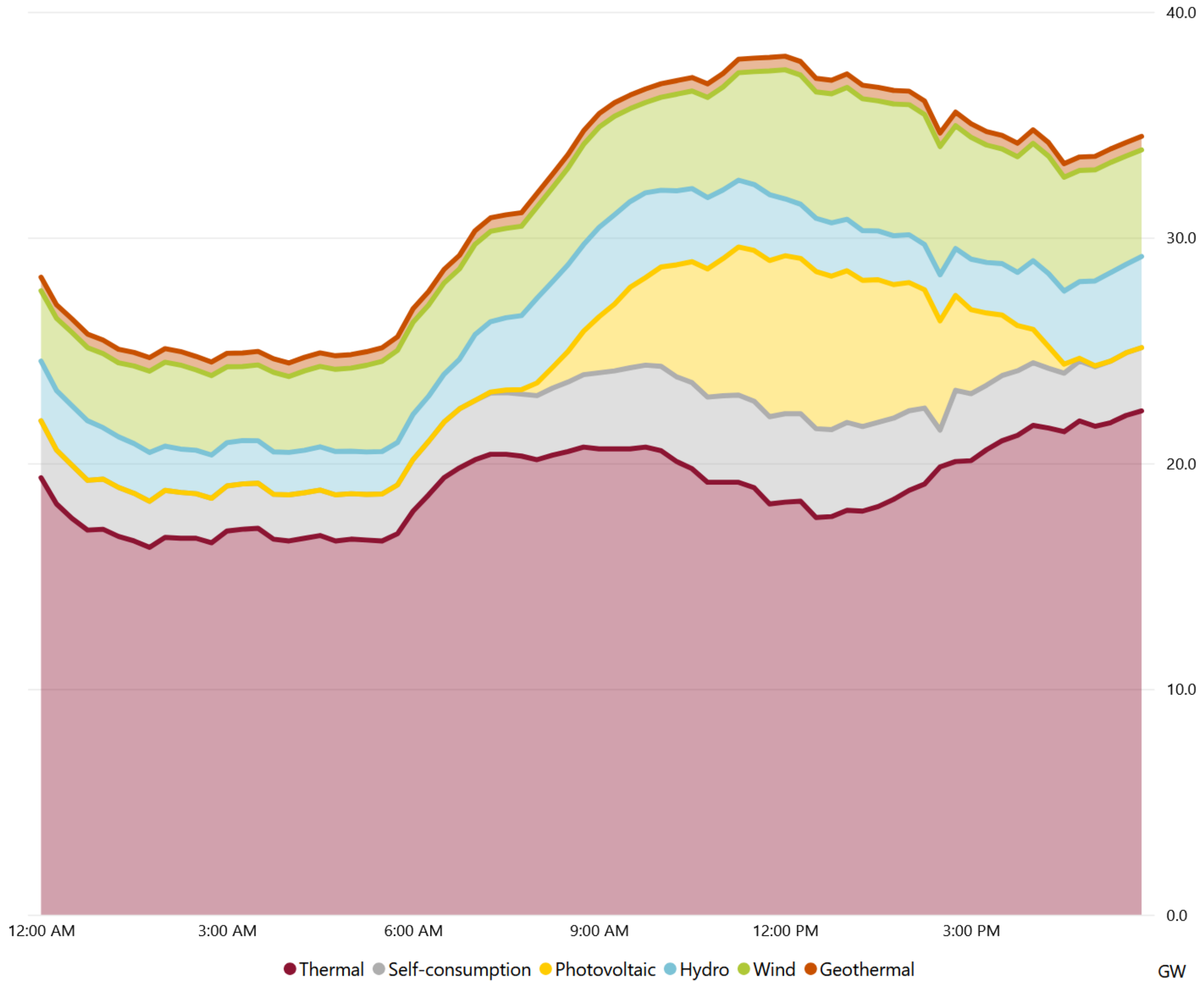
From: **24/01/2026** To: **24/01/2026**

Last update: 24/01/2026 17:45



Actual Generation
per primary source [GWh]

Thermal	**340.5**
Wind	**79.0**
Self-consumption	**50.8**
Hydro	**47.7**
Photovoltaic	**38.1**
Geothermal	**10.8**



"Baseload" Stabile con capacità di modulazione e cogenerazione

- **Produzione 24/7:** A differenza di sole e vento, le centrali nucleari producono energia in modo continuo e prevedibile, giorno e notte, con qualsiasi condizione meteorologica. Questo garantisce la "produzione di base" (baseload) necessaria per la stabilità della rete.
- **Altissimo "Capacity Factor":** Un reattore moderno opera a piena potenza per il 90-95% del tempo. Si ferma solo per brevi periodi (ogni 18-24 mesi) per la ricarica del combustibile e la manutenzione programmata. Ma è in grado di seguire il carico con variazioni fino al 5%/min.
- **Scudo contro la Volatilità dei Prezzi:** Una volta costruita la centrale, i costi operativi sono bassi e molto prevedibili. Il costo dell'uranio incide solo per una piccola parte (spesso <10%) sul prezzo finale dell'elettricità. Questo protegge consumatori e imprese dalla volatilità estrema vista sui mercati del gas o del petrolio.

Resource Availability

- Uranium Resources
- - Global distribution of identified recoverable conventional uranium resources

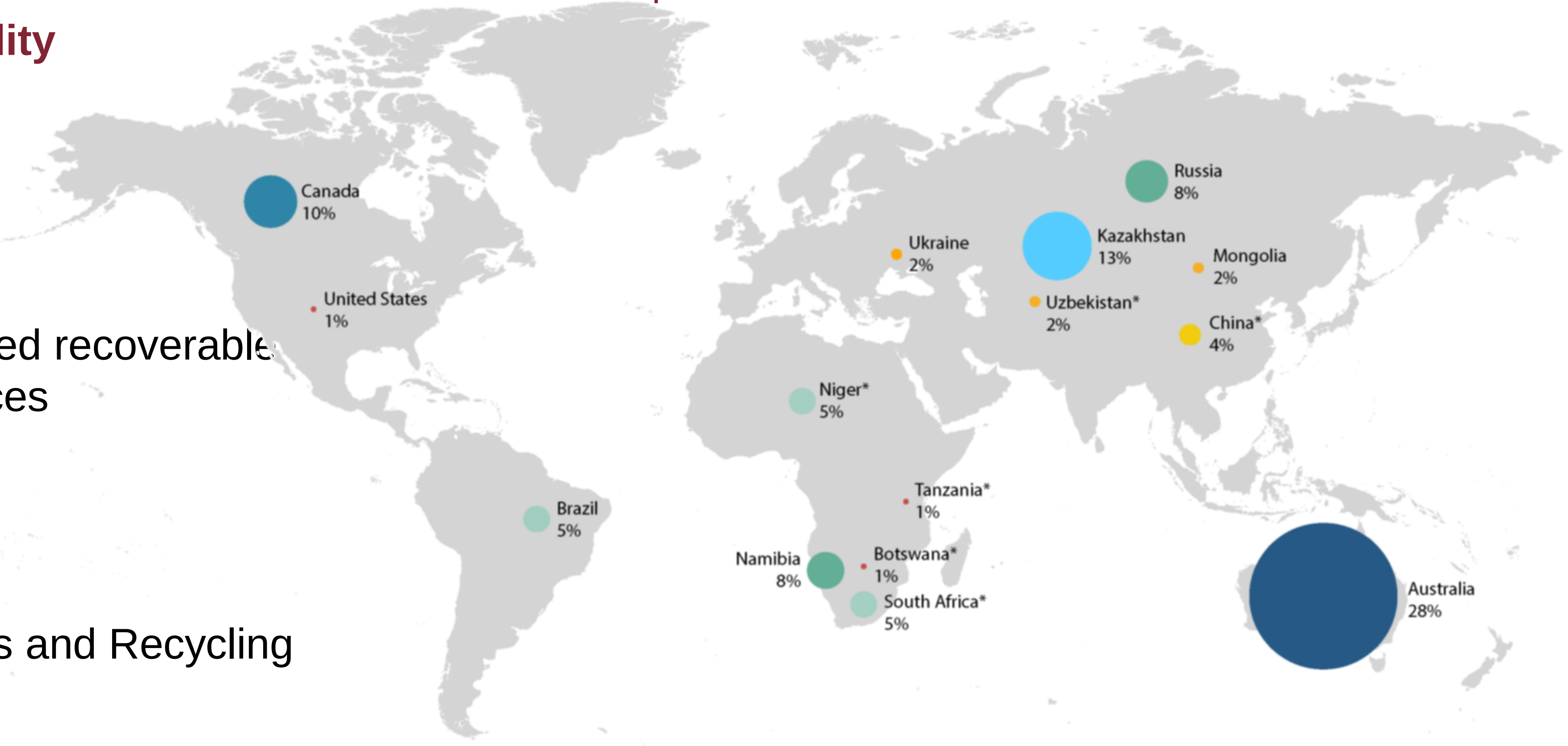
- Enough for long time…

- … and after Breeder Reactors and Recycling Spent Fuel

- Enhanced resource utilization in fast reactors

- and Thorium … after U, or U from the ocean…, or fusion…

Map of uranium reserves distribution



Materiali Critici (CRM - Critical Raw Materials) (t/TWh)

Materiali Critici (CRM - Critical Raw Materials), ovvero quelli definiti "strategici" da UE e USA perché sono:

- Scarsi (difficili da trovare in quantità sufficienti). Es. FV ha assorbito quasi il 25% di tutto l'argento estratto dalle miniere nel 2023. Trend in peggioramento
- Geopoliticamente a rischio (filiere controllate da pochi paesi, es. Cina, Congo).
- Economicamente impattanti (il loro prezzo determina il costo dell'energia).

Tecnologia	Rame	Terre Rare (Nd, Pr, Dy)	Li, Co, Ni, Si, Ag, Grafite	Rischio Geopolitico (Supply Chain)
Gas (CCGT)	~1	0	~2 (Ni)	**Basso** (sui materiali)
Nucleare	~1	0	0	**Minimo** Uranio ben distribuito
Eolico Onshore	~40	~0,2	~10 (Ni)	**Medio** Dipende dai magneti (Cina)
Solare FV	~100	0	~60 (Si) + ~0.4 (Ag)	**Medio-Alto** Silicio/Wafer (97% Cina), Cile (Li)
Eolico Offshore	~130	**~1,0**	~10 (Ni)	**Alto** Rame + Monopolio Terre Rare
Ren.+ Batt.	~900		**~200 (Li) + ~850 (grafite)**	**Molto Alto** Cina (Batt) + Congo (Co) + Cile (Li)