- The Royal Institute for Strategic Studies. Rabat, Morocco -

Coupling Nuclear Energy with Renewables for Hydrogen

Focus on Synergies, Particularly with Green (Pink) Hydrogen Production, and Integrated Energy Systems

Event: The Future of Nuclear Power in Morocco: Challenges of it's Integration into the National Energy Strategy, 24-25 April 2025
Avenir du nucléaire au Maroc: enjeux de son intégration dans la stratégie énergétique nationale
Session 2: State of the Art Worldwide Regarding the Integration of Nuclear Energy in Green Hydrogen Production

Rev 0

Morocco and Nuclear - A Snapshot

- Abundant nuclear fuel - 7 million tonnes uranium, and 30,000 tonnes of Thorium => thousands of years of energy independence.
- Focus on water production (desalination) and distributed power supply.
- 2022 - New research reactor planned with Rosatom.
- 2015 - IAEA INIR Program. IAEA supports 1 GW nuclear facility (since Grid is ~10 GW).
- 2009 / 1980's - Part of the energy mix since 1980s and re-confirmed 2009.
- 2003 - Maamora Nuclear Research Centre (2 MWt TRIGA reactor since 2009).
- 2001 - Renewed Section 123 Agreement with USA (signed first in 1980).
- 1980's - Sidi Boulbra identified in 1980's a suitable site, Studied by IAEA and French engineers 1990's 2000's.
- 1950's - Nuclear applications for medical, agricultural and industrial sectors.

CNESTEN TRIGA Mark II, La Maamora, Kenitra, Morocco

Global Energy Consumption - 620 Exajoules

- Fossil fuels: ~80%

  (*1/3rd as liquid fuel for transport, 2/3rds electricity generation, roughly split between coal, natural gas and oil*).
- Hydroelectric: ~7%
- **Nuclear: ~5%**
- Wind: ~4%
- Biomass: ~3%
- Solar: ~1%
- Geothermal: < 1%

Exajoule, EJ = 1 x 10^18 Joules. Peta 15, Tera 12, Giga 9, Mega 6

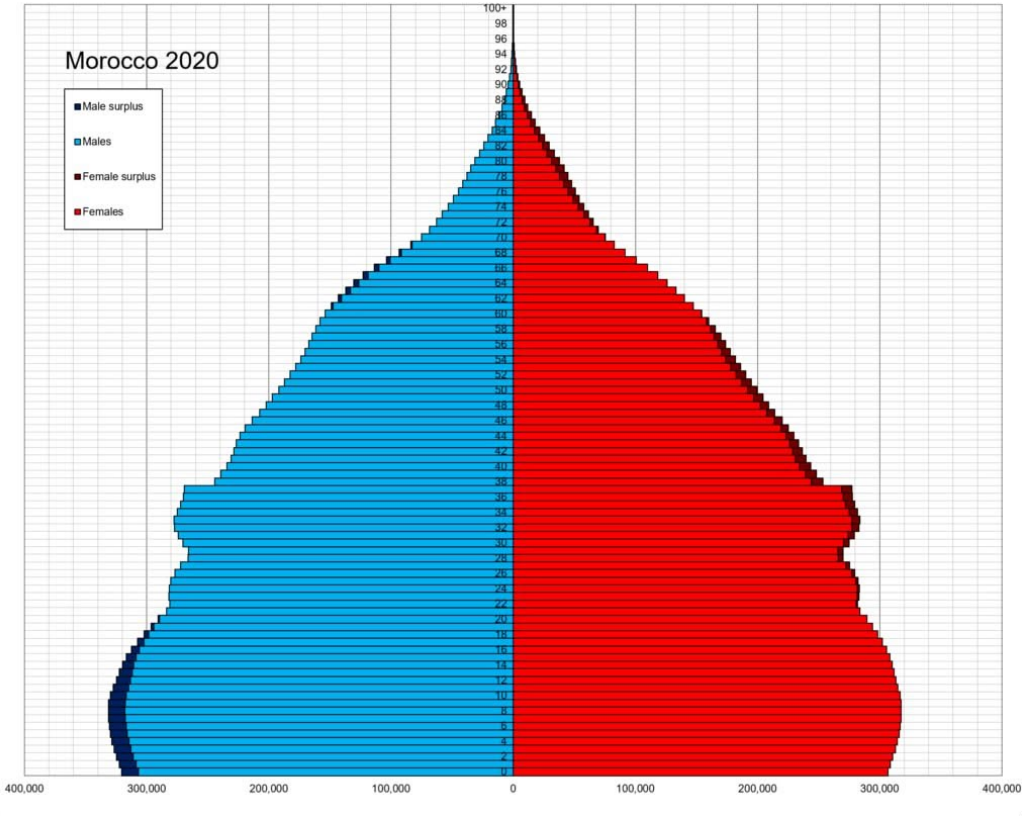
1 GWh = 3.6×10^{-6} EJ

Morocco Energy Consumption - 1 Exajoule

- Fossil fuels: >90%
  - 25% Transport (primarily liquid fuels for vehicles)
  - 40% Fuel input for electricity generation (producing about 0.15 EJ of electricity with Coal (4.3 GW installed, Capacity Factor, CF, 70%) and Gas (0.9 GW installed, CF 50%)
  - ~18% Residential & Other Heating
  - ~7% Industry Heating (fuel used in industrial processes)
- Hydroelectric: ~3% (1.8 GW installed, CF 30%)
- Wind: ~3% (2.4 GW installed, CF 37%)
- Solar: ~0.6% (1.5 GW installed, CF 13%)
- Biomass: < 1%
- **Nuclear: 0%**

Morocco - Demographics

- ~37 million people
- Arab 2/3rds and Amazigh (Berber) 1/3rd
- Fertility rate of 1.97 children per woman as of 2024.
- Boom times for Morocco for the next 30 years, then entering decline
- GDP USD 150 Billion



Fossil Fuel - Financial and Social Costs to Morocco

- >90% of Morocco's energy comes from fossil fuels (oil, coal & gas)
- Oil and Petroleum Products: ~USD 6 billion per year, ~12 million tonnes, 44% consumed by transport.
- Coal: ~USD 1.5 billion per year, 10 million tonnes
- Natural Gas: ~USD 0.5 billion per year, 1 billion cubic meters
- Air pollution costs: USD 1.1 billion USD per year (~1% GDP)

Nuclear Energy – A Strategic Opportunity for Morocco

- Replace Fossil Fuel (Coal) Demand over 10 to 15 years. **~5 GW**
- Strategic partnerships for low cost technology (eg China & Russia)
- Electrification and liquid fuel manufacture, eg hydrogen (4 m tonnes) and/or ammonia (24 m tonnes) for the transport sector. **~30 GW**
- Require **35 GW** electrical generation (CF 90%)
- China builds nuclear plants ~USD 2 million per installed MW
- CAPEX USD 70 billion
- French nuclear example: 75% energy share, ensuring energy security
- Hydrogen and Ammonia Plans Already Underway in Morocco

Liquid Fuels - Morocco's Clean Air Answer

- USD 32.5B approved hydrogen projects (ammonia / industrial fuels).
- Dahamco: USD 25B ammonia plant at Dakhla, 1M tonnes/year by 2031, export-focused.
- OCP Group: USD 7B green ammonia facility near Tarfaya, 1 million tonnes/year by 2027 & 3 m tonnes/year by 2032.
- Up to 30,000 ha land per project for renewables and electrolysis under Morocco’s Green Hydrogen Offer.
- Strategic partners: UAE’s TAQA, China’s UEG & China Three Gorges, EU firms TotalEnergies, Engie, Acwa Power => more projects.

Global Renewable Trends & Lessons from Germany

Germany > €1 trillion:

- CO2 emissions => no change
- Energy prices => twice nuclear France
- Industry => leaving
- Coal => turning back on
- Nuclear => restart?

Global trend: developer hesitation for wind and solar projects

Ouarzazate Solar Power Station (OSPS) - Noor نور

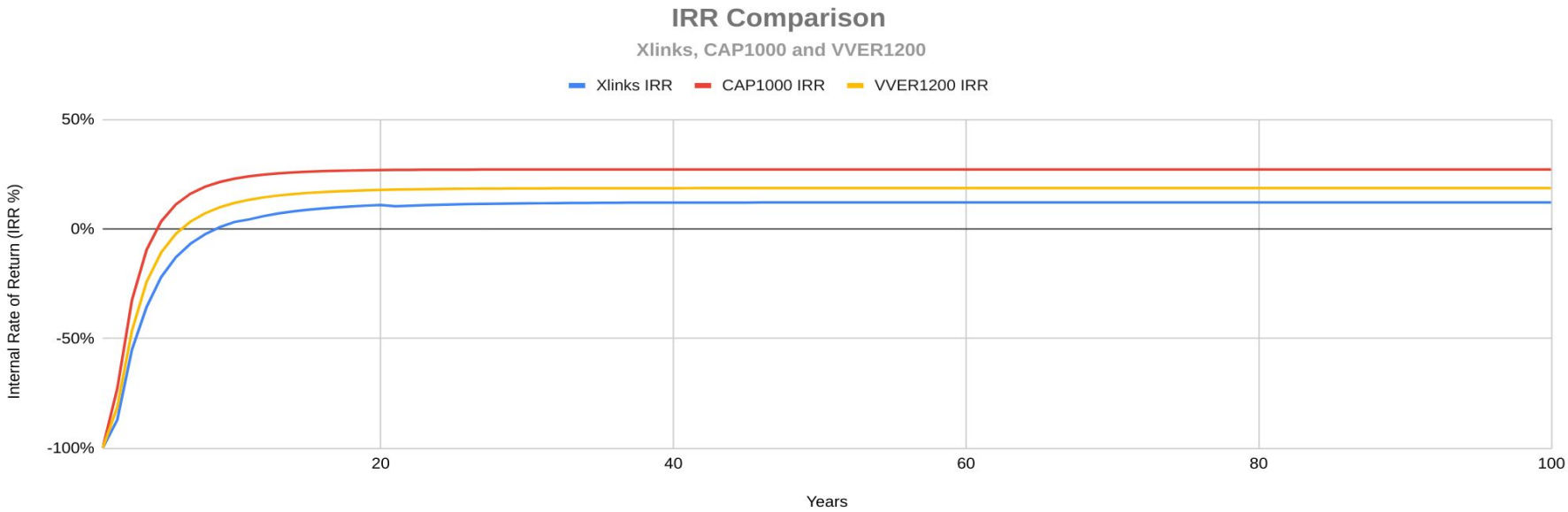
- Nameplate capacity: 580 MW installed
- Equivalent capacity: 133 MW firm supply (23% capacity factor)
- CAPEX of USD 9 billion

=> USD 68 million per useful-MW

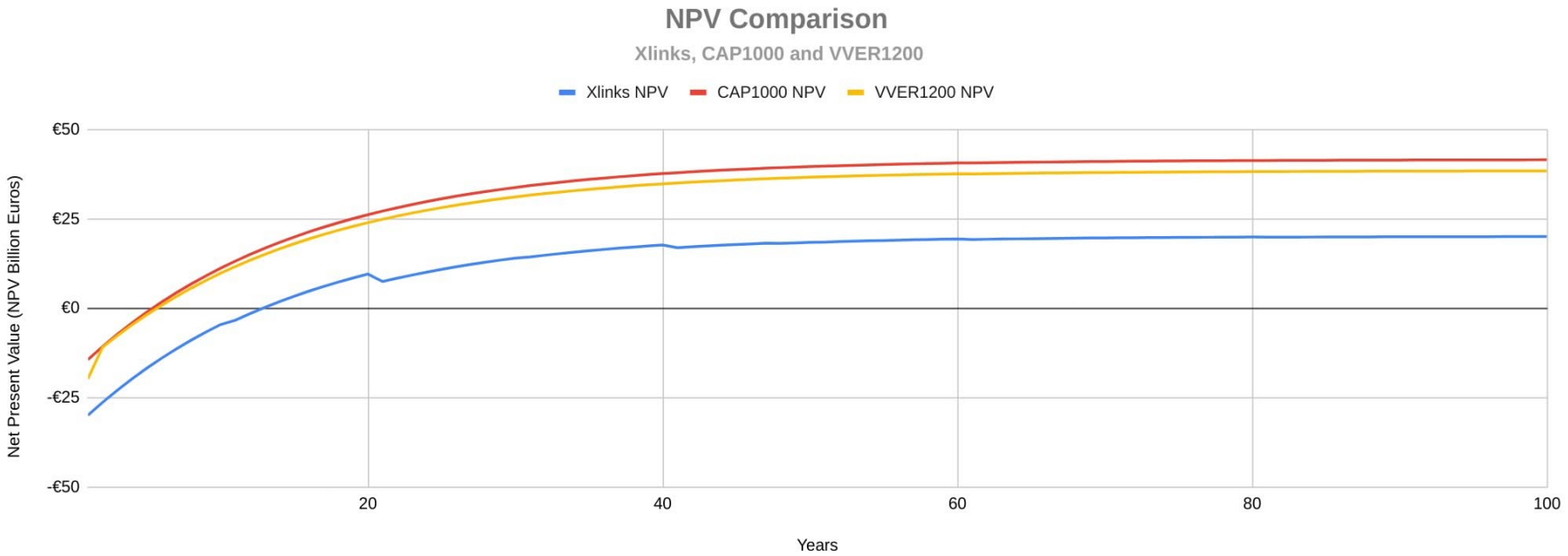
- Compare to CAP1000 from China at ~USD 2 million per MW or VVER1200 at USD 5.5 m/MW

But: Valuable Molten Salt Experience => Liquid Fission

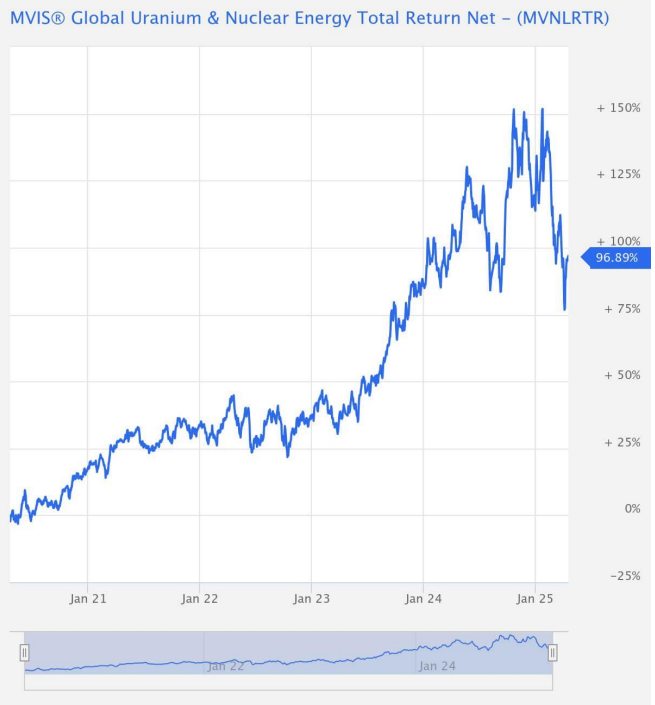
IRR - Xlinks cf CAP1000 and VVER1200

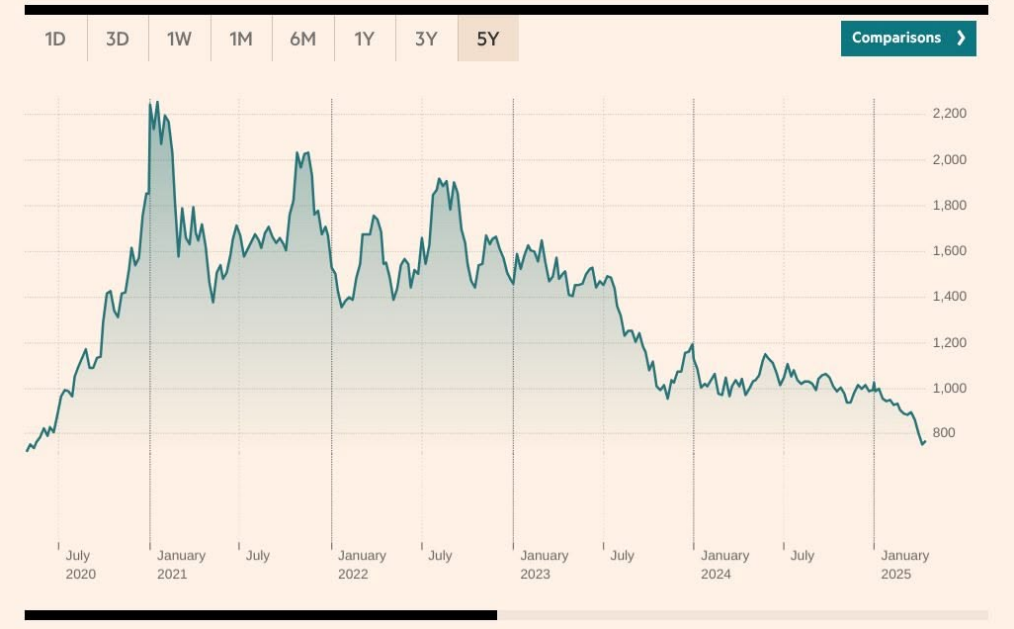


NPV - Xlinks cf CAP1000 and VVER1200



Nuclear Energy Index (MVNLRTR) vs RENIXX World





Industry Trends and Market Realities

- Renewables: Major fossil fuel companies (Shell, BP, ExxonMobil) scaling back renewable investments.

- Nuclear West: Consultants and safety experts benefit from prolonged nuclear regulatory processes, slowing progress.

- Nuclear East: Russian and Chinese streamlined nuclear construction avoids excessive consultancy overhead, driving down costs.

Hydrogen – The Small Molecule with Big Challenges

- Hydrogen is an excellent energy carrier (3x oil, 6x ammonia)
- Incompatible is with existing natural gas and liquid fuel infrastructure.
- Cannot be transported via existing gas pipelines, road tankers or ships.
- Requires entirely new storage and distribution systems.
- Morocco ~USD 5 billion required for storage, pipelines and end user interface for 100% liquid fuels replacement (4 million tonnes/year of hydrogen).

Strategic Synergies – Nuclear and Renewables with Green / Pink Hydrogen

- Nuclear provides stable, large-scale power to complement intermittent renewables
- Enables continuous green / pink hydrogen production via water electrolysis and high temperature electrolysis.
- Methane Pyrolysis - advanced technology produces **~USD 1 per kg hydrogen** with high value graphene byproduct. (IPRI.Tech). Requires stable continuous electricity.

Positive Outlook – If Renewables and Hydrogen Infrastructure Mature

If renewables become cheaper and more reliable, and hydrogen storage/transport solutions mature, a balanced energy mix is achievable.

Nuclear energy ensures energy security and supports green hydrogen at scale.

Morocco’s leadership in renewables can be complemented by nuclear for a resilient, sustainable energy future.

Hydrogen Costs Today

Hydrogen Production Method	Indicative Cost Range (USD/kg)	Notes
Steam Methane Reforming	0.5 – 3.5	Lowest cost, depends heavily on natural gas prices and if carbon capture is included “Grey” or “Blue” Hydrogen
Various Electrolysis Technologies	2.0 – 6.0	Alkaline, Proton Exchange, Solid Oxide (hi temp)
Green Hydrogen (Electrolysis)	3.0 – 7.0	Depends on renewable electricity cost, electrolyser CAPEX, and capacity factor. Lower bound achievable with large-scale solar and low-cost electrolysers.
High-Temperature Electrolysis	> 4	Potential for cost reduction with technology maturity and integration of waste heat; targets ~$2/kg by 2026 (DOE)
Thermochemical (Solar/Nuclear)	3.5	Emerging technology, not yet commercial.
Methane pyrolysis	1	Emerging Laboratory scale verification of technology (IPRI.Tech)

Fission Potential in Morocco

Uranium - 7 million tonnes - **6,500 years** energy supply

Thorium - 30,000 Tonnes - **1,000 years** energy supply

- No breeding and no reprocessing -

Thorium Research - A Global Trend

Shanghai Institute of Applied Physics (SINAP), China	Kurchatov Institute, Russia	Grenoble Institute of Technology, France
European Organization for Nuclear Research (CERN)	Indian Atomic Energy Commission (DAE), India	Oak Ridge National Laboratory (ORNL), USA
Canadian Nuclear Laboratories (CNL)	Idaho National Laboratory (INL), USA	Japan Atomic Energy Agency (JAEA)
Netherlands Organisation for Applied Scientific Research (TNO)	Denmark Technical University (DTU)	Texas A&M University, Nuclear Engineering & Science Center, USA
Nuclear Research Institute (NRI), Czech Republic	Brazilian Nuclear Energy Commission (CNEN)	German Research Center for Geosciences (GFZ)

Energy Density is Important

Ammonia: ~20 MJ/ kg

Petroleum Products: ~40 MJ/kg

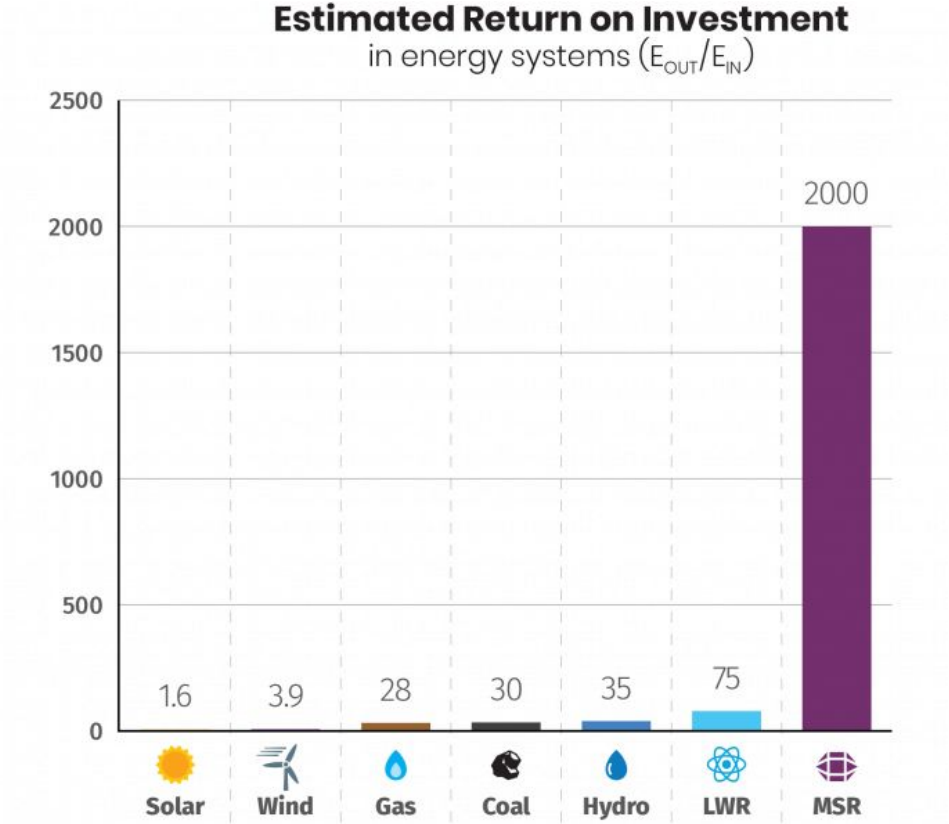
Hydrogen: ~120 MJ/kg

Uranium (natural, as used in typical solid-fuel reactors): **~442,000 MJ/kg** (practical energy extracted from natural uranium fuel)

Thorium *(fully utilised in advanced Liquid Fission Burners):*
~79,000,000 MJ/kg

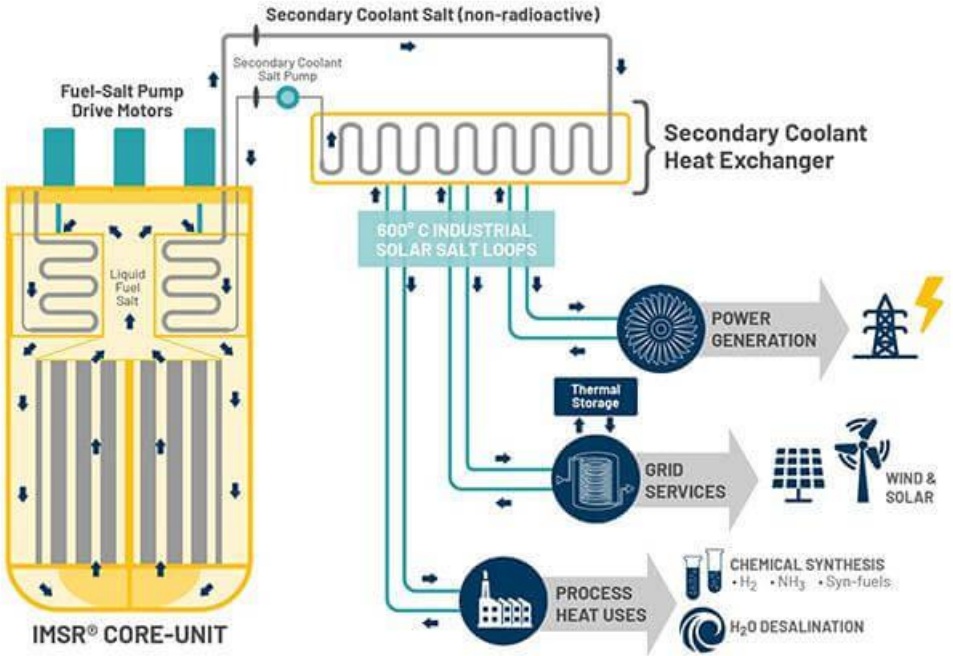
Liquid Fission (Eutectic salt) - Why it's so good

Energy Out compared with Energy In



Liquid Fission (Eutectic salt) - Why it's so good

+ No Water
+ Low Pressure
+ 100% Fuel Burnup
+ Zero long term waste
+ Fuel Flexible
+ High Temp (~750C)



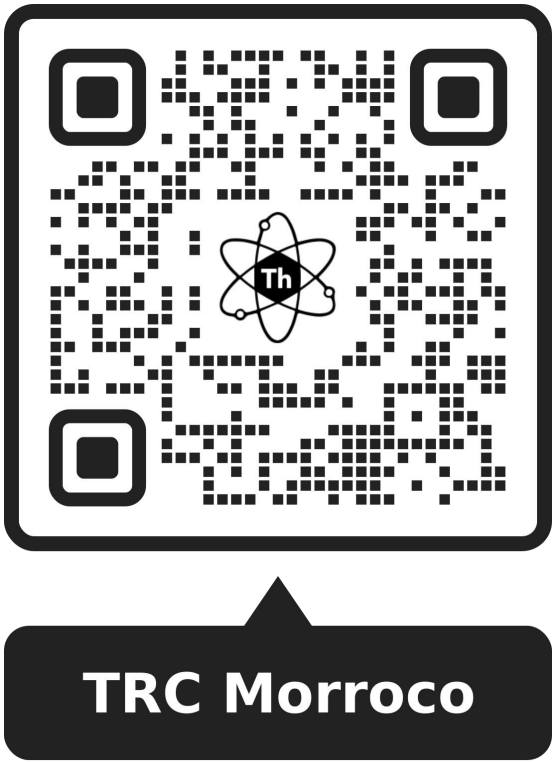
Cost of Electrical Energy

Technology	USD per MWh
Liquid Fission Thorium	10
Solar	20
Wind	20
Coal	50
Gas	60
Solid Fission Uranium	60

Thorium Research Centre

1) Industrial applications of heat - including **desalination** and **hydrogen production** (HTE)
2) Power production with CO2
3) Medical isotope Production
4) Fuel Preparation
5) Fuel Security and Tracking

https://tinyurl.com/TRC-Morocco



Morocco’s Path Forward – A Vision for 2035

- Partnerships with China & Russia for fast nuclear deployment.
- Integrate nuclear with wind/solar for baseload and hydrogen.
- Develop hydrogen distribution infrastructure.
- Position Morocco as a regional clean energy hub, exporting green energy and hydrogen/ammonia to Europe.
- Research **Liquid Fission Thorium Burner** technology for the longest term solution.

One Ship to Power the World - On Thorium

Thank You - Questions and Discussions

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This Presentation: https://tinyurl.com/TTN-Nuclear-Morocco-20250425

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