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Thorium power

Abundant climate neutral energy source

Goal:

Build and operate 2 Thorium-based power plants of +2000MWe each in Norway, start 2017

Work in progress:

1. **Technical feasibility**, development and approval of Thorium fuel-cycle and identification of suited reactor
2. Developing possible mining/processing of Thorium from the **Fen deposit** in Ulefoss.
3. Informing Norwegian public and political sector of the potential for substantial, inexpensive, **climate neutral** power plants.
4. Possible cooperation with utilities and large, **power consuming industries** for future power take off.
5. Preparations for application for **a commercial license** for building and operating a thorium power plant i Norway. Other countries might be targeted later.

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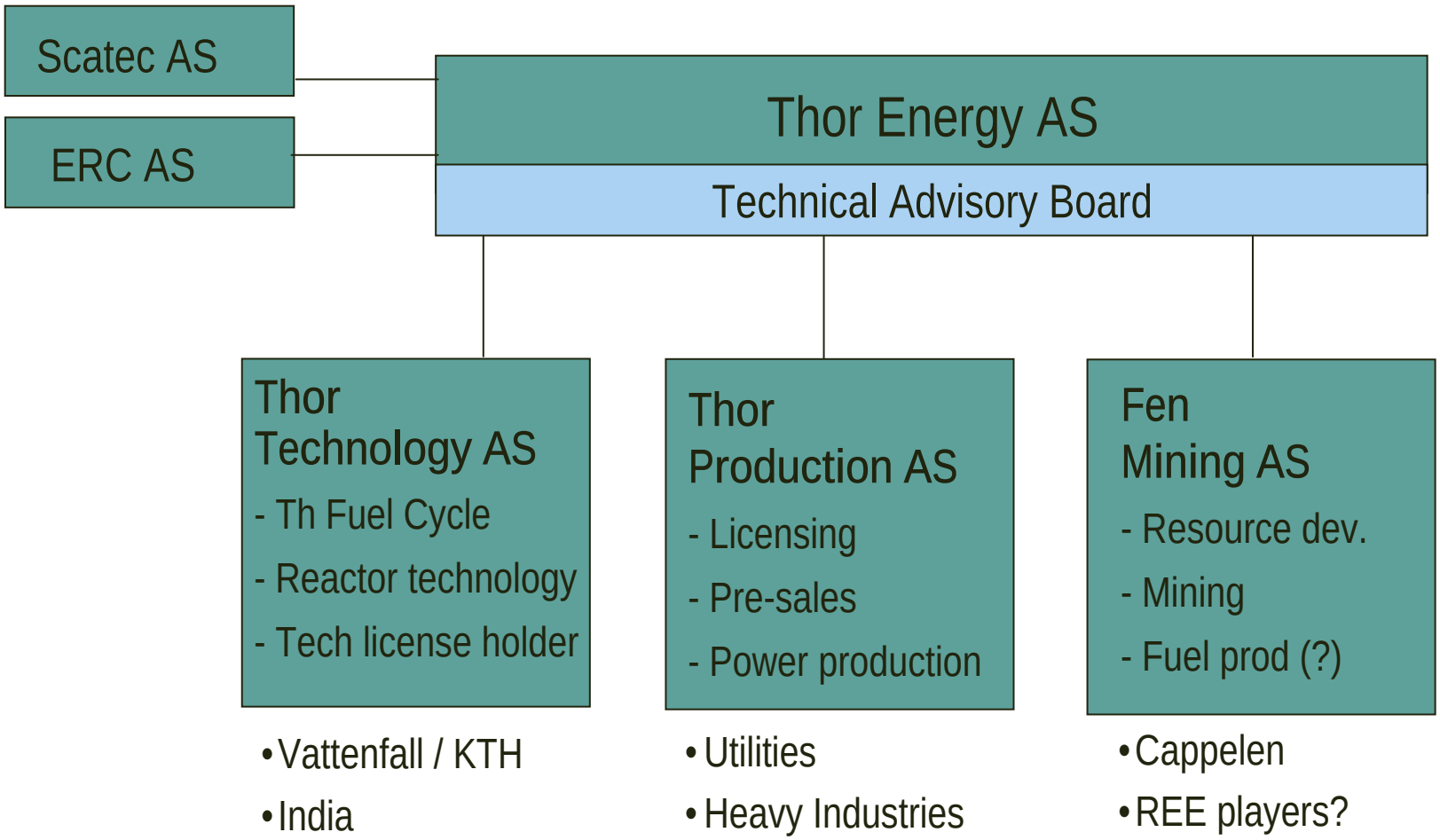

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Norway – energy nation

- The world's sixth largest hydro power producer
- The world's third largest petroleum exporter
- The world's fourth largest gas exporter
- The world's third largest Thorium reserves

- Primary industry with focus on energy
- Secondary industry with focus on energy
- Educational systems with focus on energy
- Well developed laws and regulatory agencies on energy
- Political focus on energy as base for industry and society

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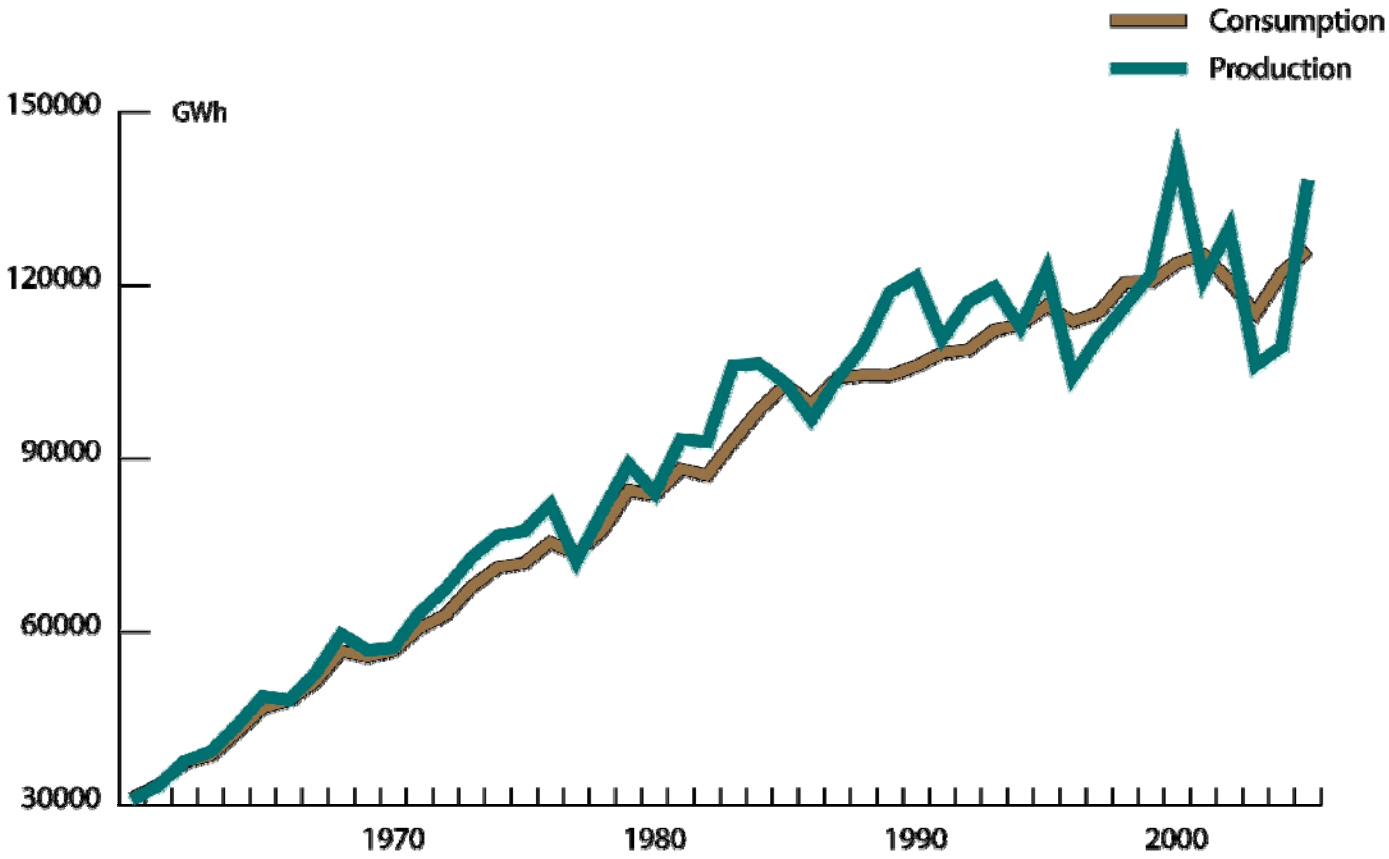
Power; consumption v. production



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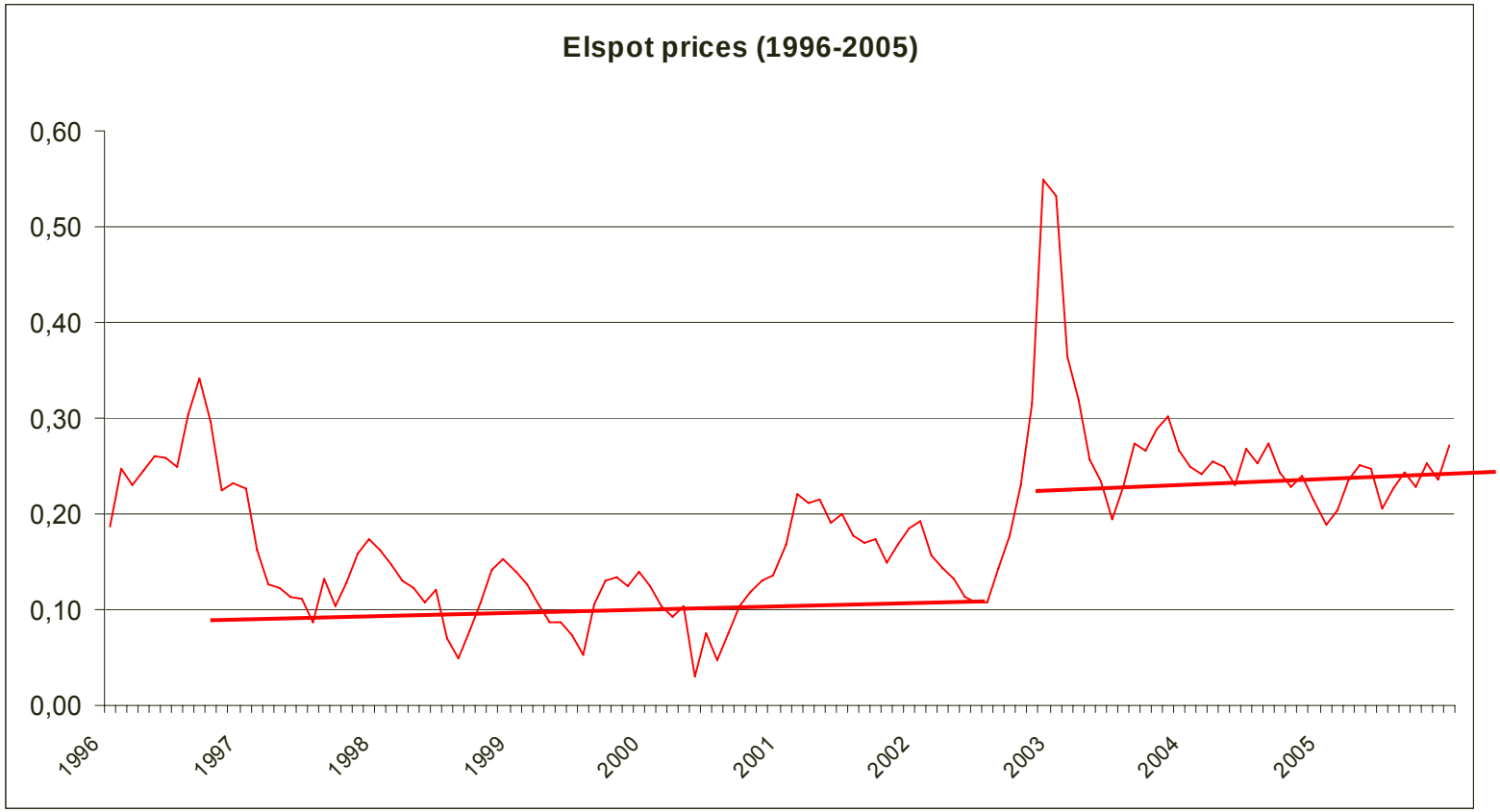
Increased price floor benefits a Thorium plant



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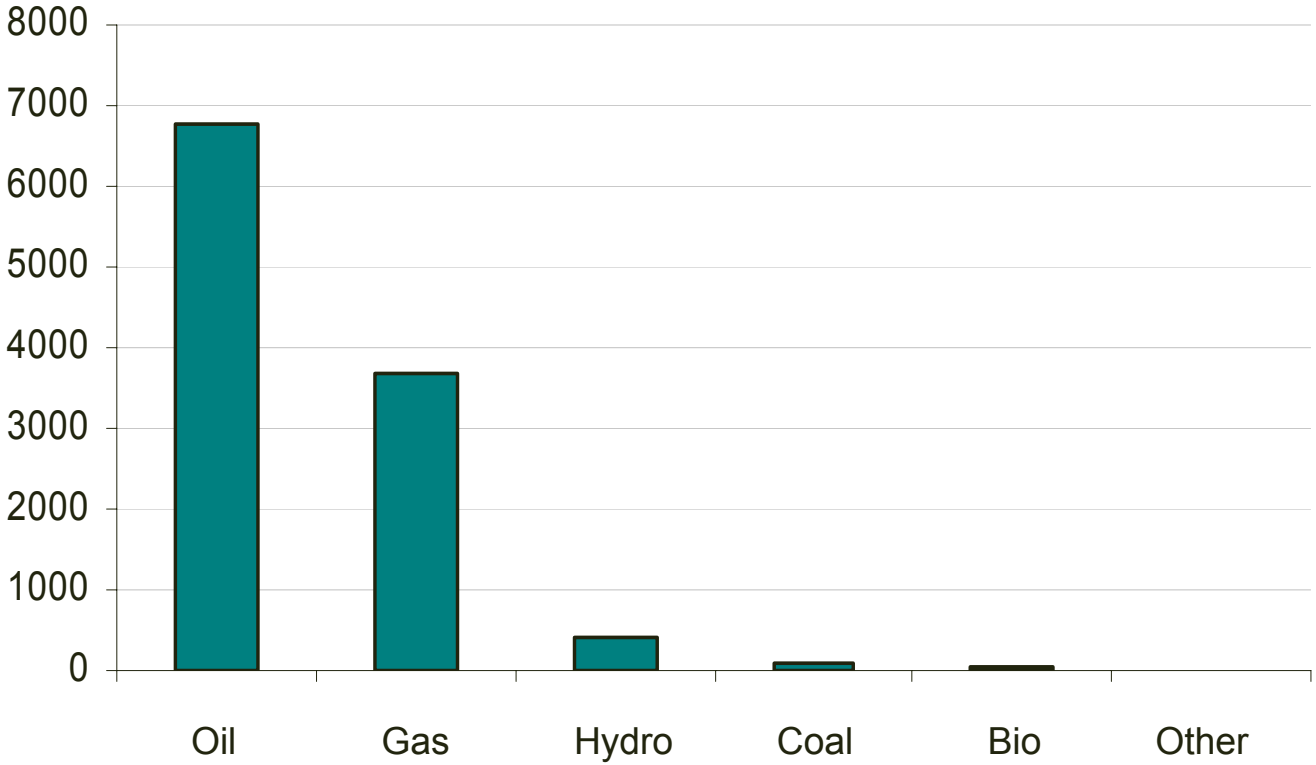
Energy Production, Norway 2004, PJ



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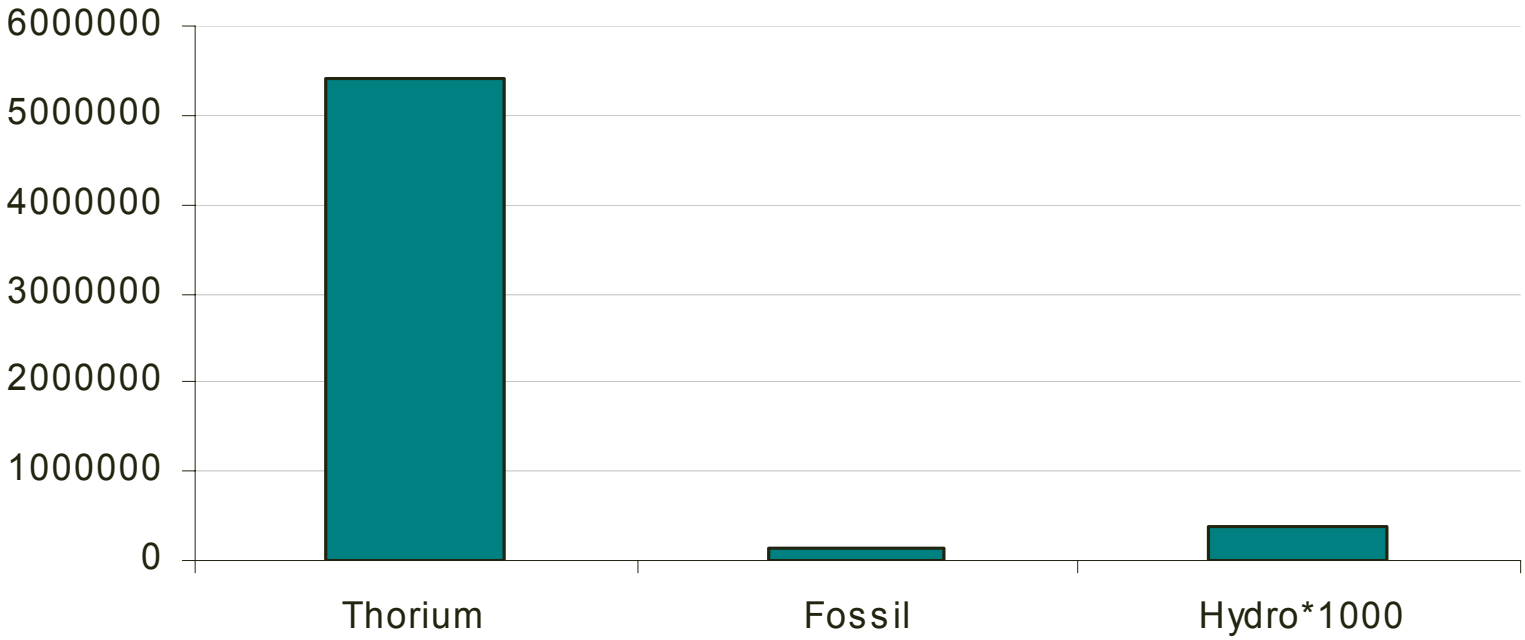
Energy Reserves, Norway 2004, PJ



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Thorium: From black to white fuel:

Uranium (UO_2)

Thorium (ThO_2)

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3 main arguments against uranium reactors

1. Risk of severe accidents – the criticality question
   - Melting of kernel
   - Tsjernobyl syndrome
2. Uranium waste as bomb material
   - Plutonium inventories
   - Proliferation issues
3. Spent fuel management
   - Safe storage issues
   - Radiotoxicity a potential danger to environment for + 100,000 years

Can a thorium fuel cycle adress these problems?

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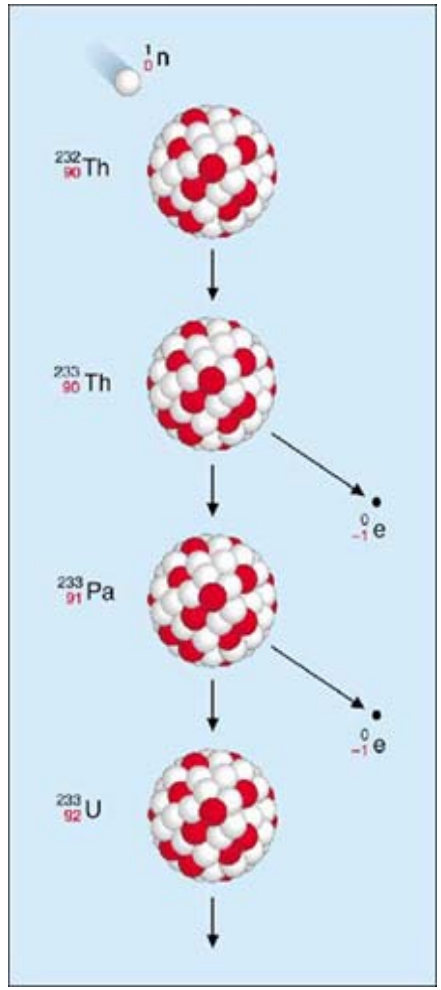
From fertile to fissile

- Natural Thorium consist of >99,9 % of the 232-isotope.
- No expensive or dirty enrichment needed
- Neutrons from seed fuel breeds the fissile U233
- Seed fuel (Pu239 or U235) needed to compensate neutron loss
- Thorium oxide has better chemical and physical properties than uranium oxide



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1. Criticality – a critical question

- All available thorium technologies have sub critical neutron economy. (neutron loss is to high)
- Fuel design crucial to achieve critical equilibrium
- Gen3 reactor hardware have high safety margins – a less potent fuel add extra safety margins
- Less (neutrons) is more (safety)!

Uranium 1,3 ← **theoretical n-surplus** → 0,5 Thorium

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2. The bomb issue

Potential fission-explosive materials

Material	Halflife (years)	Bare Critical Mass (kg)*	Fraction of transuranics in 53 MWd/kgU spent fuel
^{233}U	1.6×10^5	16.2	-
Weapon-grade U (94% ^{235}U)	7.0×10^8	49.1	-
20%-enriched U (boundary between HEU and LEU)	"	780	-
^{237}Np	2.1×10^7	57.	0.066
Weapon-grade Pu (6% ^{240}Pu, 0.01% ^{238}Pu)	2.4×10^4	10.7	
Reactor-grade Pu (27% ^{240}Pu, 3% ^{238}Pu)	"	14.4	0.824
^{241}Am	432.	60.0	0.089 (20 yrs after discharge)

Frank von Hippel, Princeton University

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Global stockpiles of fissile material (tonnes)

	Weapon U* (93% ^{235}U equiv)	Weapon Pu*	Civil Pu-2003 In-country (own)	Civil HEU (including in spent fuel)
Russia	600 ± 300	120 ± 25	38	?(10's)
USA	525 ± 70+	47	9 (2002)	?
China	25 ± 6	3.5±1.5	-	?
France	25 ± 8	5 ± 1.4	79 (48)	6.5
U.K.	8 ± 2	3.1	96 (73)	1.6
Japan	-	-	5 (41)	?
Germany	-	-	11(2002)(29)	1
TOTAL	**1200 ±350**	**180 ±25**	**250**	**≈50?**

Frank von Hippel, Princeton University

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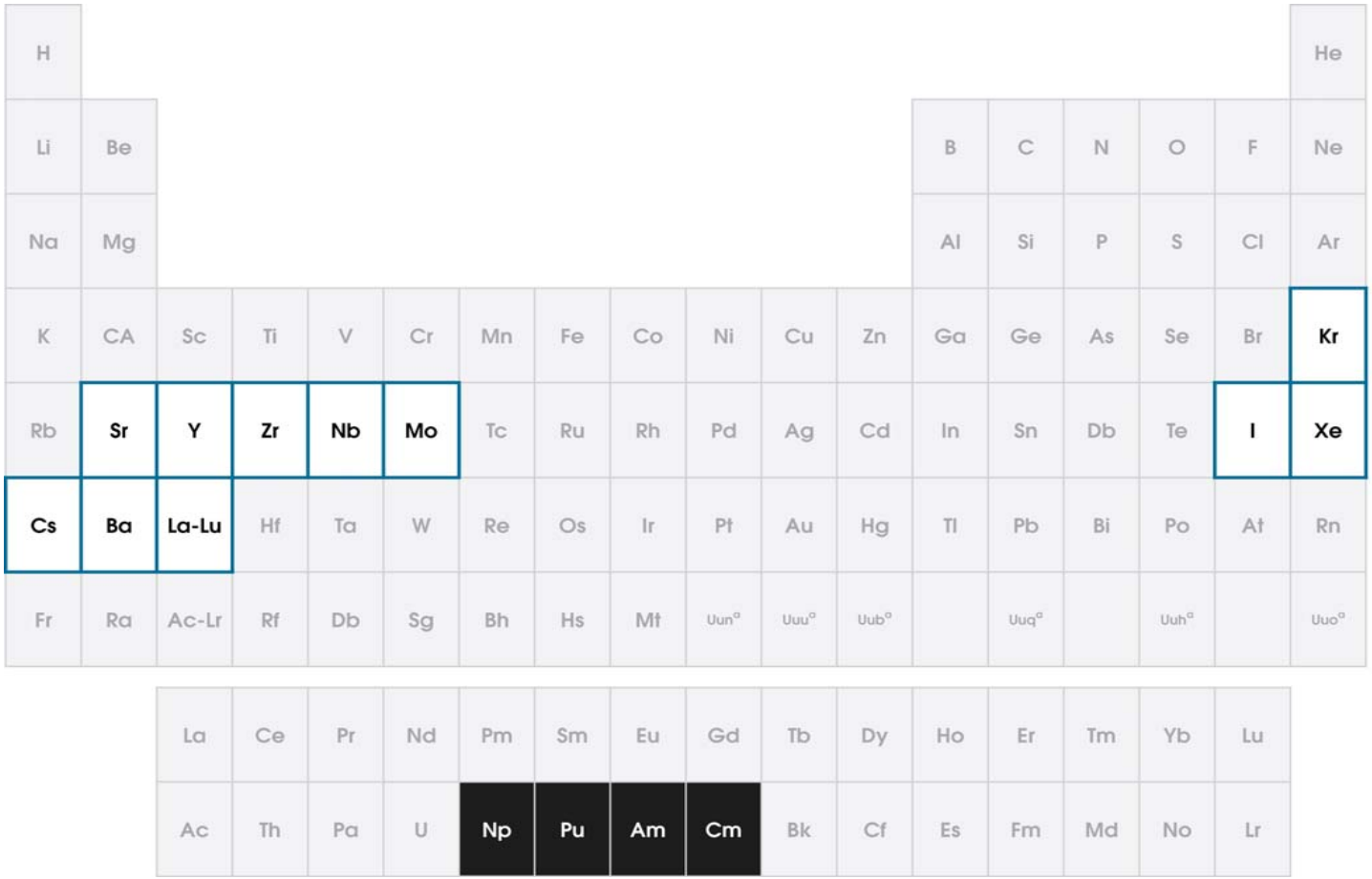
3. Waste – the big difference



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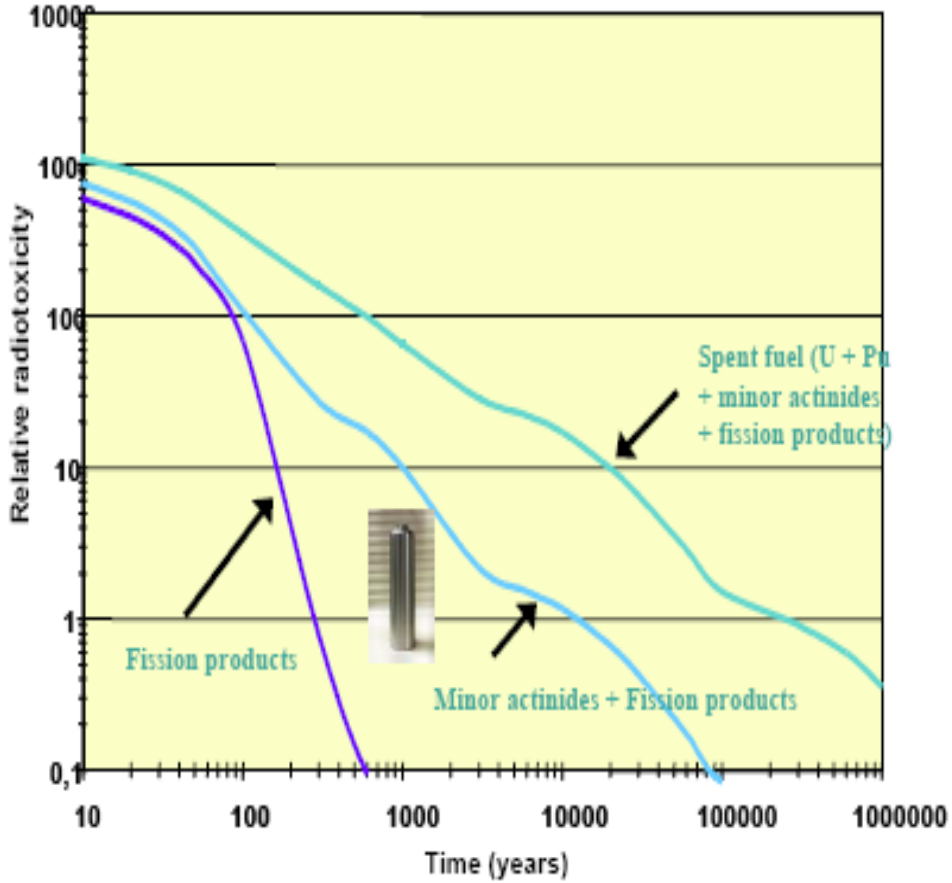
Waste characteristics

- No U238 gives almost no higher actinides
- Waste is dominated by unused fuel and fission products
- No Pu239
- Highly radioactive waste – but for few years



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IAEA, status report May 2005

….in recent times, the need for proliferation-resistance, longer fuel cycles, higher burn up, improved waste form characteristics, reduction of plutonium inventories and in situ use of bred-in fissile material has led to renewed interest in thorium-based fuels and fuel cycles in several developed countries…….

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Coal is main global radiotoxicity culprit

- Emission UK 2001, nuclear: 8,9 Bq/kWh (Electricity Association)
- Emission UK 2005, coal: 8,3 Bq/kWh (Institution of Engineering and Technology)
- Grundemmingen, Germany, nuclear: 10,7 Bq/KWh (annual report)
- Emission China, coal: 9,65 Bq/kWh (aocrp-2)

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Overall target

Develop and license a Thorium fuel cycle and reactor technology for power production based on a fuel with following characteristics:

- Max content of Norwegian Thorium
- Neutron source: Reactor-grade spent fuel
- Optimized waste characteristics

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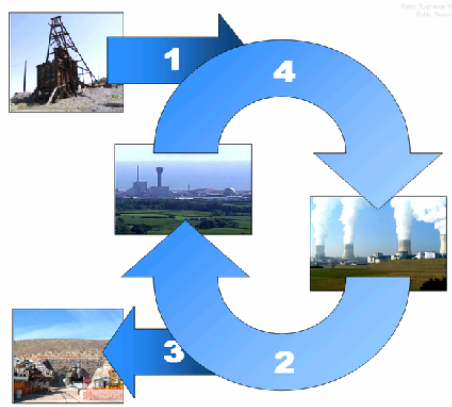
The Thorium Fuel Cycle:

- The foundation and start for all further work and power production
- Partnership with Vattenfall / KTH for one year Feasibility Study initiated
- Indian support very beneficial

1. Extraction and refinement of natural Thorium
2. Extraction, processing and refinement of fissile fuel seed material
3. Fuel composition, geometry and design
4. Fuel rod- and assembly fabrication
5. Handling and logistics of fuel assemblies
6. Reactor physics, topology and operation
7. Spent fuel handling, processing, separation and possible re-use
8. Waste characteristics, handling, storage, containment, etc.
9. Overall economy
10. Overall safety & proliferation
11. License & approval issues



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Reactor technology - directions

First generation;

1. Light Water Reactor (Westinghouse, GE, Hitachi, VVER, etc)
    - Radowsky / Thorium Power-type “seed-and-blanket fuel”
    - Conventional fuel design with Thorium-mix
2. Heavy Water Reactor (AECL)
    - Separate, demountable fuel rods
    - Mixed seed/Th fuel

Second generation;

3. PBMR, Pebble Bed Modular Reactor
4. Indian ATBR

Gen4 & breeder reactors

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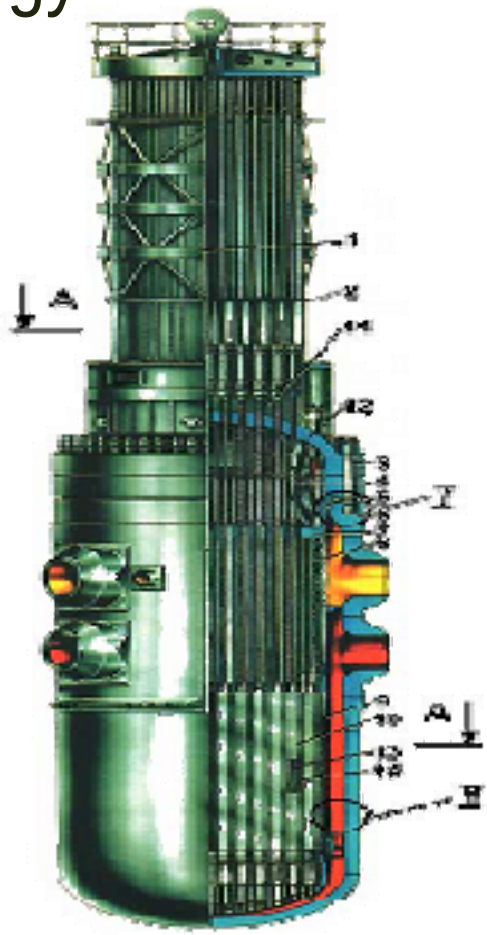
1. Light water – seed & blanket technology

- Several reactor vendors, 80 % of reactor market
- US Thorium Power Inc with Radowsky fuel design
- Close cooperation with the Russians on Pu-burnup
- 140 nuclear scientists in Russia
- Several patents on fuel composition for LWR
- Cooperation agreement with Westinghouse
- Israel is developing new Radowsky design
- Several utilities interested; possible burnup of Pu & lowered fuel cost



www.thoriumpower.com

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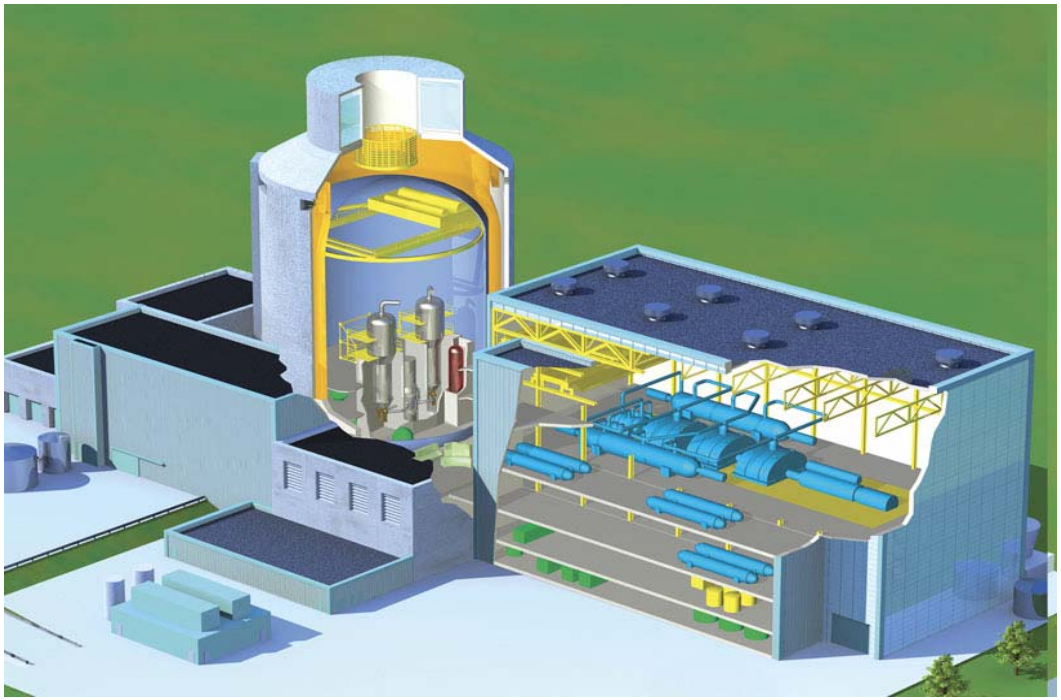
Westinghouse AP 1000



Key data:

- Certified by NRC
- Investment of ~4 billion US$ for 2 reactors on one site
- Active/passive safety
- 17-18 TWh
- 20-30 øre/kWh
- Pu seed & Th blanket

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2. Heavy water – mixed fuel

- Only one reactor vendor on the market; Candu
- Candu has no military history
- High efficiency: full on-power refueling
- Very good neutron economy – needs low addition of seed fuel.
- Readily available technology. Extensive testing and documentation for several seeds (LEU, HEU, rgPu).
- No physical changes or process alterations needed for Th/once through cycle.

Canflex fuel bundle

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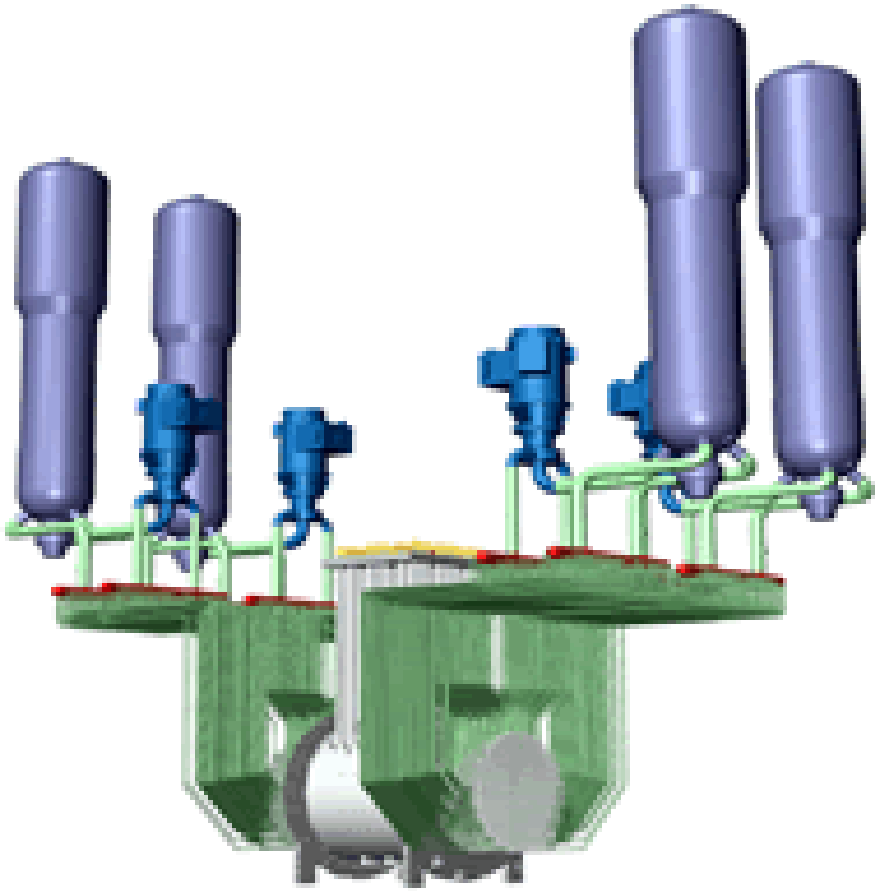
AECL Candu ACR



Key data:

- Certified by NRC
- Investment of ~4 billion US$ for 2 reactors on one site.
- 17-18 TWh
- 20-30 øre/kWh
- Separate seed (LEU, HEU or rgPu) og Th rods in matrix or mixed fuel

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3 & 4 Pebble bed & Fast breeders

- Extensive experience on both U & Th pebble bed reactors on research level – very good results. Efficient, high temperature reactors. No reactor vendors as of now – long certification process. Probably very good option after 2020/2030.

- India has extensive research on thorium breeders.
  - Uranium scarce, coal expensive, Thorium abundant
  - Presently building a 500 MW ATBR
  - Possibly close to a commercialization of their ATBR (2012?)

- Other fast breeder technologies might come, based on gen4 research (Areva, Hitachi etc.)

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4. Indian ATBR design (600 MW)

Reactor power	MWe	600
	MWt	1875
Total core flow	(tonnes/h)	27,000
Average heat rating	(w/cm)	172 (neglecting thoria clusters)
No. of (ThO2 + PuO2) fuel clusters in the core	360	
No. of natural ThO2 clusters in the core	120 (fixed) + 25 (moveable) = 145	
No. of fresh fuel assemblies per batch	120 (seeded) + 120 ThO2 (no seed)	
Active core height	(mm)	3600
Average fuel temperature	°C	600
Average coolant temp. (Boiling H2O – 70 kg/cm2)	°C	286
Coolant inlet sub cooling	(kcal/kg)	7 to 20
D2O – Moderator temperature	°C	80
Radial D2O reflector thickness	(mm)	600 to 700
Axial D2O reflector thickness	(mm)	600
Calandria tank size	(m)	~8.4 dia ´ 4.8 height

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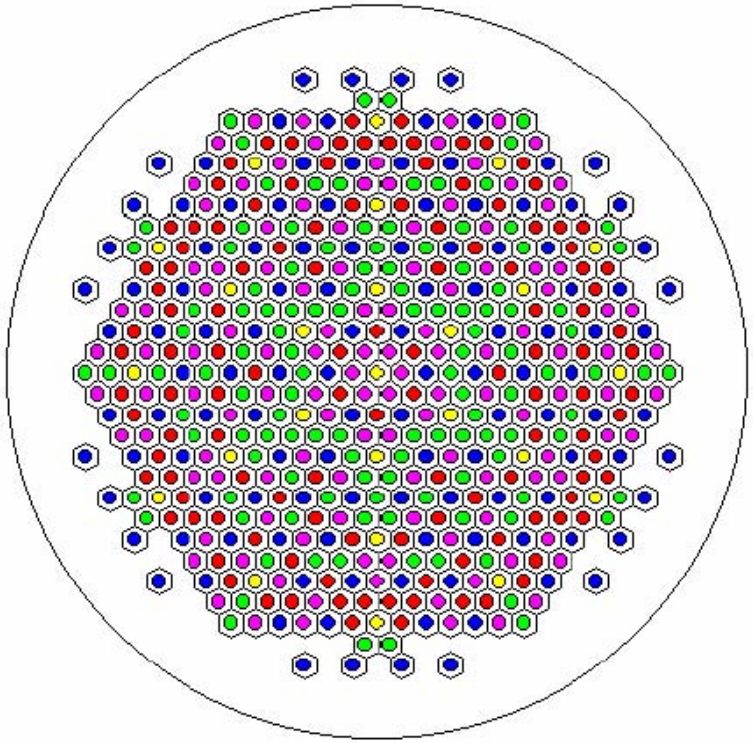
Indian ATBR with Pu-seed



600 MW ATBR needs
550 kg Th/year

Expected to cost 25 ø/kWh when ready for commercialization in 2012

- Seed (PuO2-ThO2)Cluster – Cycle 1 120
- Seed (PuO2-ThO2)Cluster – Cycle 2 120
- Seed (PuO2-ThO2)Cluster – Cycle 3 120
- Fresh ThO2 (Fixed) – 120
- Fresh ThO2 (Movable) - 25

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Is power from Thorium cost efficient ?

- No adequate numbers, but unlikely to be surprising.
- Oak Ridge estimates Thorium reactors to be 5-10 % cheaper in operation than U-235. (1 øre/kWh)
- Low fuel cost and high finance cost give foreseeable cost structure compared to fossils.
- Expected Norwegian Thorium kWh-cost: 20-30 øre/kWh (running cost 8-10 øre, the rest is financing)

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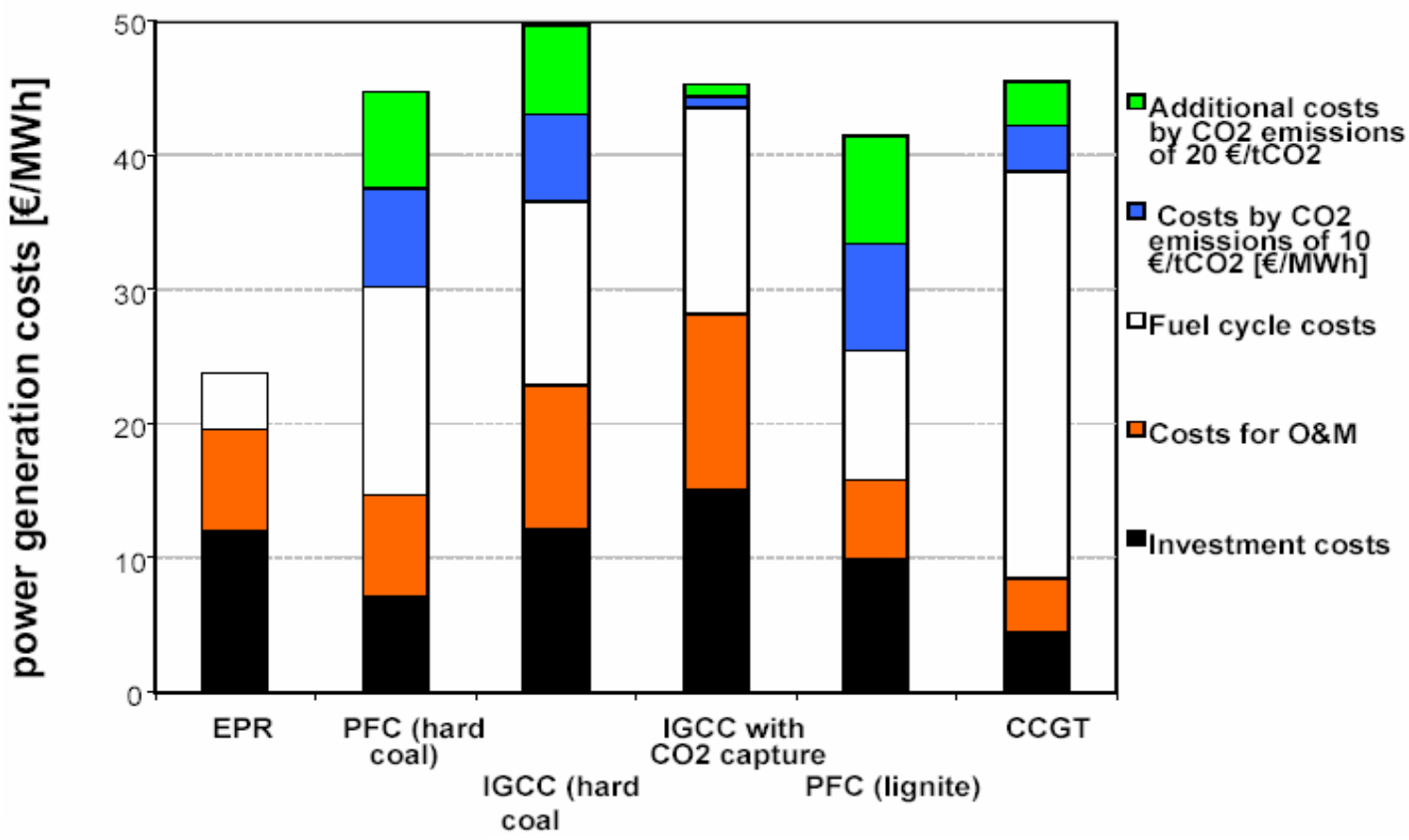
Future European power generation cost



Univ. of Stuttgart

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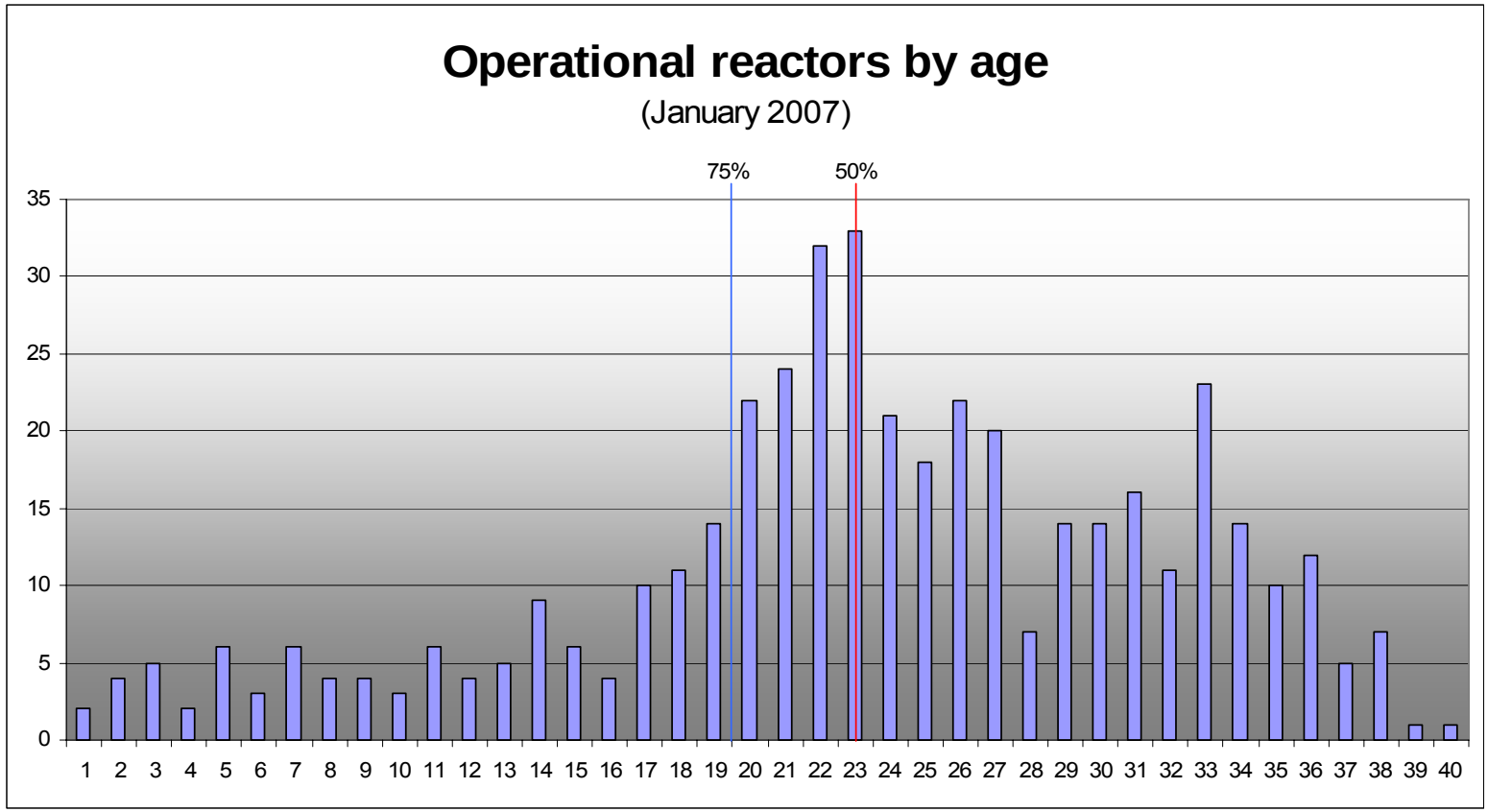
Uranium plants closing to retirement….



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Conclusions Norway – thorium power

- Norway a leading energy nation – from oil & gas.
- Norway an electrified nation – No. 1 in electricity consumption/capita.
- Norwegian hydroelectric power a superb power resource for Europe.
- Norway has enormous Thorium resources (>1.500.000 TWh)
- A Norwegian thorium power plant is feasible – from a technical and financial point of view. Competitive cost.
- 17-18 TWh low cost power may be available in 10 year – if welcomed
- Norway may reargue its nuclear position
- No Thorium power in Norway without political support

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