Hvordan dekke verdens femtidige energibehov

Bergen Rotary, januar 2018

Egil Lillestøl

1

- Verdens befolkning og energibehov øker,
- energi fra fossilt brennstoff produserer CO_2
- økende CO_2 i atmosfæren øker den globale temperaturen
- kull, olje og gass er viktige inntektskilder

Dette er hovedingrediensene i en bokstavelig talt brennbar debatt der oppfatningene og interessene er sterke og tilsynelatende motstridene, kunnskapene mangelfulle, og der foreslåtte løsninger ofte bidrar til å øke problemene heller enn å bidra til å løse dem

2

Verdens befolknng 31 oktober 2011:
7 milliarder
og idag ca
7.6 milliarder
og med en doblings-rate på litt under 50 år

See for eksmpel lenkene:

http://www.worldometers.info/world-population/

og http://www.worldometers.info/fr/

3

Globale befolknings - projeksjoner 2020 - 2050
(i milliards 10^9) (*)

	total	**urban**
2020	**7795**	**4338**
2025	8893	**5394**
2050	**9771**	**6339**

forventet: 10 milliarder i 2055

(*) **vær oppmerksom på bruken av stor og kort skala:**
stor skala: 1 million = 10^6, 1 milliard = 10^9, 1 billion = 1 million million = 10^{12}, 1 trillion = 1 million million million = 10^{18}
kort skala (UK, US og andre) 1 billion = 10^9, 1 trillion = 10^{12}

4

For å redusere problemene forbundet med den skremmende befolkningsøkningen og hjelpe til å unngå en global krise for mennesker og annet liv på kloden, trenger vi kraftige tiltak innen energiøkonomisering kombinert med ny utvikling og massiv bruk av

solenergi
vindturbiner
høytflyvende drager, og
- kjernekraft basert på nye teknologier

MEN,
sol- og vindkraft **varierer med vær, vind** og tid på døgnet og må bakkes opp av "støttekraft"
med tilsvarende kapasitet (cfr. EROEI), og
den eneste energi-"kilden" med slik kapasitet er kjernekraft.

Så enten vi liker det eller ei blir ikke spørsmålet:
ja eller nei til kjernekraft, men hvilken kjernekraft vi skal velge

Termisk Energi-tetthet for forskjellige brennstoff (*)

Brennstoff	**MJ/kg**	**MJ/l**
Antrasitt kull	33	72(*)
Diesel/fyringsolje	46	39(*)
Bensin	47	35(*)
Biodiesel	42	31(*)
Ved	6 - 17	2 - 3(*)
Naturgass	54	0.038 (**)
Kjerne-fisjon (U-235)	77 000 000	1 500 000 000

(*) Når vi går fra termisk til elektrisk energi, må disse tallene multipliseres med effektivitets-faktorer mellom 30 og 45 %

(**) Dette tallet er for ukomprimert gass. Om komprimert til 200 bar, er tettheten 10 MJ/l

Norges-energibalanse 2016 (GWh)	
Total Produksjon	**141 968**
Vannkraft	143 417
Varmekraft	3 456
Vindkraft	2 116
Import	5 741
Eksport	22 151
Brutto Konsum	**132 579**
Pumpelagring og annet konsum	1 435
Tap og statistiske forskjeller	7 697
Netto Konsum	**123 447**
Gruvedrift og produksjon osv.	54 761
Tjenester	26 539
Private hjem og jordbruk	42 147

Salg av ren-energi- sertifikater (*)

Den norske befolkning trodde Norge war **Grønn**

se det utrolige dokumentet:

http://www.abcnyheter.no/penger/okonomi/2016/07/09/195228156/751-prosent-av-norsk-stromforbruk-i-2015-var-fossil-og-atomkraft

som forklarer at 75.1% det norske energikonsumet
i 2015 kom fra kjernekraft of fossilt brennstoff

(*) dagens parallell til middelalderens avlatsbrev

Katolsk Biskop som gir messe-deltagerne kollektiv avlat

Malt av Lorenzo Lotti, Italia, 1524

9

Globalt energikonsumption trenger store tall :

(se http://en.wikipedia.org/wiki/Giga-)

kilo (k) = 10^3
Mega (M) = 10^6
Giga (G) = 10^9
Tera (T) = 10^{12}
peta(P), exa(E), zetta(Z)...

1 år = 8766 timer (h) (bruk 9 000 h)

1 kW_e kontinuerlig forbruk i ett år ca 9 MWh

1 GW_e kontinuerlig forbruk i ett år ca ~ 9 TWh

10

OECDs energi-definisjon:

thermisk (varme)-verdi for olje
1 toe (1 tonn olje-ekvivalent) =
thermisk verdi av 1 tonn olje (42 GJ)

Mtoe (= Megatonn o.e.) (42PJ)

OECD bruker en effektivitetsfaktor på
38% fra thermos til elektrisk energi (*)

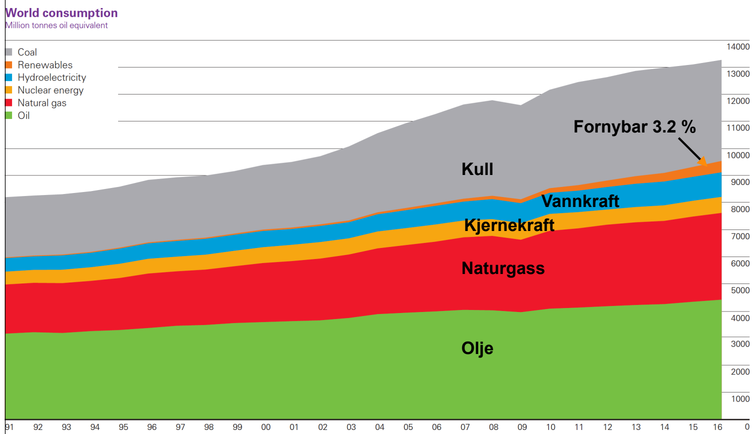
2 Mtoe ≈ 1 GW_e x år ≈ 9 TWh

(") Noe å tenke på når vi diskuterer elektriske biler !!!

11

Global årlig energi-produksjon (Mtoe) for 1991 – 2016

Gejnnomsnittlig vekst: 2.1 % pr. år (doblingsrate 33 år)



12

Noen tall (Mtoe) for perioden 2013 - 2016:

	2013	2014	2015	2016	R/P y
Total Globalt Kons.	12807	12928	13147	13276	
Olje	4179	4211	4331	4418	< 51
Kull	3967	3882	3840	3732	153
Naturgass	3053	3066	3152	3204	< 53
Totalt fossil	11199	11159	11323	11323	

Globalt kons. opp: mer enn 3 % pr år fra 2001 til 2006,
+ 5.4 % fra 2009 til 2010, (krftigste økning siden 1973),
1.0 % hvert år fra 2011 til 2016 (*)

1 % svarer til en doblingsrate på ≈ 69 år.

Land	Befolkning (millioner)	Totalt Energi-kons Mtoe	Konsum toe pr hode	Økning 2016/2015
Kina	1412	3053	2.17	2%
India	1346	724	0.51	6%
Afrika	1070	440	0.41	2%
US	324	2273	7.0	-0%
Verden	7587	13276	1.75	1%
Norge	5.1	49	9.17	3%

En normal dag i Shanghai


minst 500 000 dødsfall pr. år fra luftforurensing i Kina

Sml med Europa der det er beregnet at helsekostnader knyttet til luftforurensinger fra kullbrenning beløper seg til rundt 43 Milliarder pr. år

Globale "påviste" reserver av fossilt brennstoff (BP2017) (*)

Med dagens konsumsrate har vi

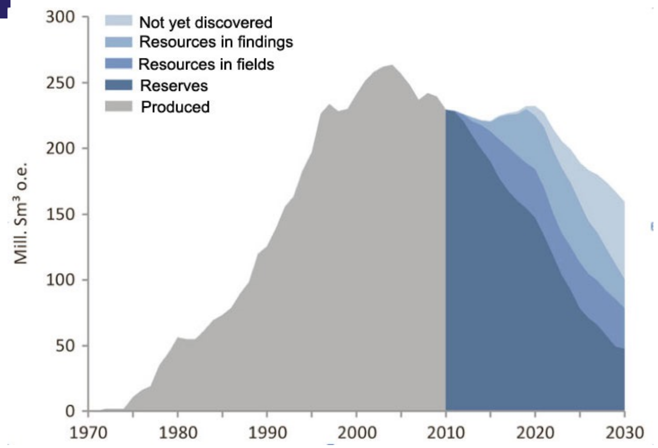
olje og gass for ca 51 år og
kull for ca 114 år

Med en forventet dobling av konsumet innen 2070, og ved å anta at konsumet vil bli dreidd over mot kull, vil reservene av fossilt brennstoff være meget begrenset i siste halvdel av dette arhundret

(*) BP Statistical Review of World Energy, June 2017, (BP2017):

https://www.bp.com/content/dam/bp/en/corporate/pdf/energy-economics/statistical-review-2017/bp-statistical-review-of-world-energy-2017-full-report.pdf

Det norske olje- og energi-departmentet
Ressurs-rapport 2011 (1Sm³ = 0.84 toe)
Produsert og solgt i året 2012: 230 Mill. Sm³ oljeekvivalenter



Viktige spørsmål:

Hvordan skal Norge dekke sine energibehov i siste del av dette århundret ?

Eller kanskje viktigere:

Hvordan skal Norge betale for sin import ?

Vær oppmerksom på at om vi idag tok bort alle inntekter fra petroleums-eksport, ville Norge ha et underskudd på sin betaligs-ballanse på rundt 140 milliarder Nkr, eller ca 25 000 kr pr nordmann

Kan fornybar energi dekke våre fremtidige energibehov?

For nye energiløsninger må vi sikre oss at energien som produseres er større enn energien som går med til bygging og vedlikehold av installsjonene (inklusive energilagring)

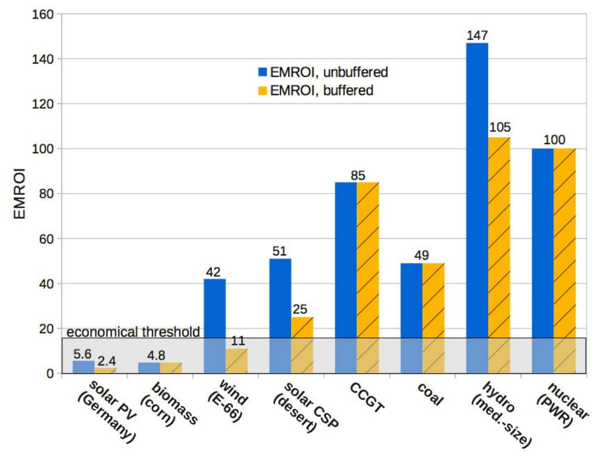
Det er de siste årene publisert en mengde artikler om dette, og der man diskuterer forholdet

$$R = EROEI = E_R/E_I \text{ } (E_R \text{ Over } E_I)$$

Det er klart at dette forholdet i alle fall må være større enn 1, og vi må også ta med energien som går med til oppbakkings-installasjoner som batterier, vannreservoarer (for pumpelagring) osv

På neste slide en studie av Weissbach

EMROI for forskjellige energiløsninger (Weissbach)



(*) CCGT : Closed Circuit Gas Turbine

Og for å understreke alvoret, her en studie fra Sveits og som tar for seg solpaneler

Artikkelen:

photovoltaic solar systems in regions of moderate insolation:
finnes på lenken
http://www.sciencedirect.com/science/article/pii/S0301421516301379)

og konkluderer at PV-installasjons ved slike breddegrader går med energitap

og her er flere lenker for de spesielt interesserte

EROI (Energy Return On Invested)
eller EROEI (Energy Return On Energy Invested)

http://festkoerper-kernphysik.de/Weissbach_EROI_preprint.pdf
(meget detaljert, men noe vanskelig)

http://mahb.stanford.edu/wp-content/uploads/2014/03/energy-policy_Hall_Lambert_Balogh_2013.pdf

og an fullstendig, relativt "lett å lese", artikkel
http://theenergycollective.com/barrybrook/471651/catch-22-energy-storage/

Utfra slike studier kan vi trekke en bastant konklusjon:

"Alle" fornybare energiløsninger er nødvendige om vi skal unngå en alvorlig global energikrise i andre halvdel av dette århundret

Imidlertid, er de fornybare løsningene kostbare og variable og vil bare gi energigevinst om de bakkes opp av tilsvarende mengder med basiskraft. Og den eneste ikke-fossile basiskraften med tilstrekkelig kapasitet er kjernekraft.

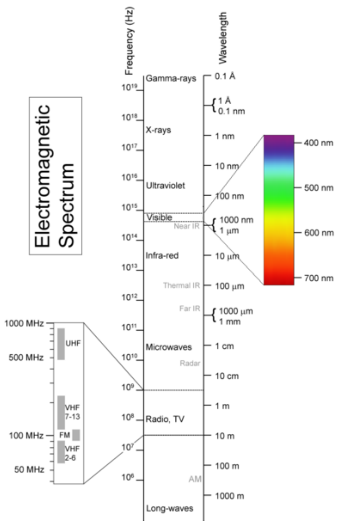
Spørsmålet blir derfor ikke ja eller nei til kjernekraft, men HVILKEN kjerkraft vi skal velge.

En ting er derfor sikkert: ny kjernekraft er nødvendig, men basert på ny teknologi

Men et stort hinder for utvikling og bruk av kjernekraft er en utstrakt redsel for alt som har med kjernkraft å gjøre:
RADIOFOBI

Hvordan har dette problemet oppstått og hvordan kan det kurerers?

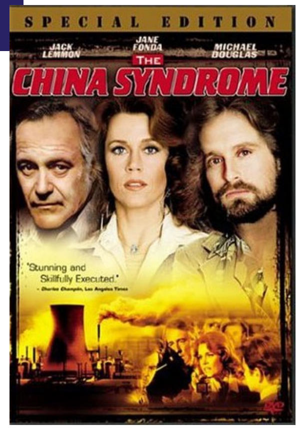
Electromagnetisk spektrum



Farlig, men hvor farlig?

Inge fare ???

Mobiltelefoner
Mob. tel.- antenner
Wi-Fi
Mikrobølgeovner
Høyspenningslnjer
MRI
……….



Radioaktiv stråling

Skremmende fiksjonsfilm basert på en imaginær kjerne-reaktor Katastrofe,
US-premiere 16 Mars, 1979

12 dager senere:

Three Mile Island “ulykken”
28 Mars, 1979

Three Mile island ulykken:

Ingen kort- eller langtids helseeffekter funner,

MEN,
klart observerbar **radiofobi** og **nocebo** effekter:

Anti-kjernkraft-demonstrasjoner etter Three Mile Island ulykken og det hjelper ikke med ulykker som Tjernobyl

og nå senere Fukushima

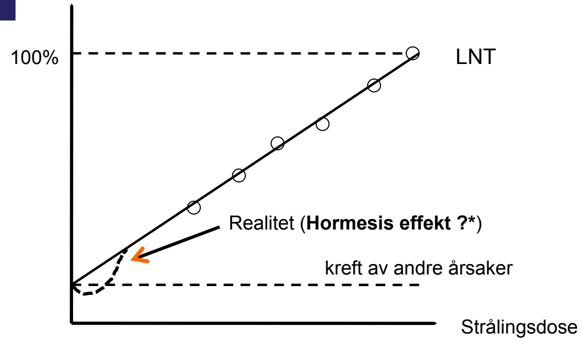
29

Men hvordan ser realitetene ut?

Antall døde pr TWh for forskjellige energi-kilder		
Kull	161	26% av verdens energi, 50% of electricity
Olje	36	26% av verdens energi
Naturgass	4	21% av verdens energi
Biofuel/masse	12	
Torvmasse	12	
Solpaneler (tak)	0.44	mindre enn 0.1% av verdens energi
Vind	0.15	mindre enn 1 % of world energy
Vannkraft	0.10	Europe, 2.2% av verdens energi
Vann inkl. Banqiao	1.4	ca 2500 TWh (171000 Banqiao-omkomne)
Kjernekraft	0.04	5.9 % av verdens energi

30

Kreftdødelighet (strålingsmyndighetenes bidrag til radiofobi)



LNT-modellen versus nyere “realitets”-baserte studiesr

(*) https://en.wikipedia.org/wiki/Hormesis

31

en Kohortstudie fra Taiwan (W.L. Chen, 2006)

Et stort antall hus i Taipei, Taiwan, satt opp i 1983,
hadde benyttet resirkulert stål sterkt kontaminert med radioaktivt kobolt.
Husene hadde et stort antall leiligheter der det bodde rundt 10 000
mennesker over en periode på 20 år og som mottok betydelige
strålingsdoser.

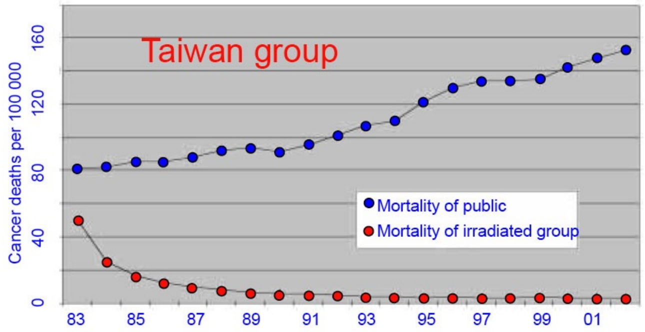
Siden leilighetene hadde forskjellige nivåer av stråling, var det mulig
å studere hesle-effektene fra forskjellige akkumulerte stråldoser.

The surprising result of the study is shown on the next slide

Det overraskende resultatet er vist på neste slide

32

En Cohort studie fra Taiwan:



and Chen's conclusion on the next slide:

Og her må jeg av tidsmessige grunner skifte skriftspråk

Nuclear Fission

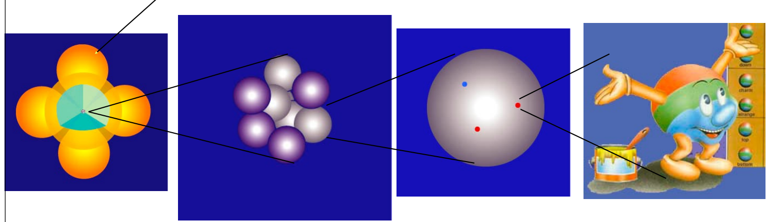
Today we have close to 20 000 years of accumulated running experience of commercial nuclear reactors.

An accident like the Chernobyl accident is simply not possible (by design) for a modern reactor.

First a few slides excursion into the atom

Components of matter

Electrons (10^{-18} m) see



Atom	nucleus (proton or neutron)	nucleon	quark (q)
10^{-10} m	10^{-14} m	10^{-15} m	10^{-18} m

Comparison of

Energy from Chemical Reactions and from Nuclear Reactions

Nuclear fissions release millions of times more energy per unit of weight than chemical reactions

Nuclear fission based on Uranium, Plutonium and Thorium

Uranium, U, is a heavy and radioactive element with 92 protons in its nucleus.
Natural Uranium has two isotopes, ^{235}U (0.7%) (with 143 neutrons) and ^{238}U (99.3%), (with 146 neutrons)
Only ^{235}U is fissile (and is also used in nuclear bombs)

Plutonium, Pu, has 94 protons in its nucleus and is produced from ^{238}U in nuclear reacors.
The two highly radioactive isotopes, ^{239}Pu and ^{241}Pu, can both be used in nuclear reactors and in nuclear bombs.

Thorium, ^{232}Th, is a low radioactivity element with 90 protons (and 142 neutrons) in its nucleus
It can be transformed by neutron bombardment to fissionable ^{233}U which can be used in nuclear reactors,
but only with great difficulties in inefficient nuclear bombs

Uranium and Thorium

^{235}U: half-life 700 million years
^{238}U: half-life 4.5 billion (10^9) years
^{232}Th: half-life 14 billion years
only ^{235}U is fissile and represents about 0.7% of natural uranium, so enrichment is necessary. (*): explain nest slide

Uranium is soluble in water and Thorium is not.
Combined with the half-lives this gives an estimate of somewhere between 4 and 6 times more Thorium than Uranium in the Earth's crust –

and Thorium gives about 200 times more energy per kg compared to Uranium in a "critical" (**) reactor.

(**) criticality to be discussed in a few slides

Enrichment

is a process where the ratio of ^{235}U/Uranium is increased from 0.7% to for instance 8% in a reactor, or up to above 60% for a nuclear submarine reactor and even higher for a nuclear bomb.

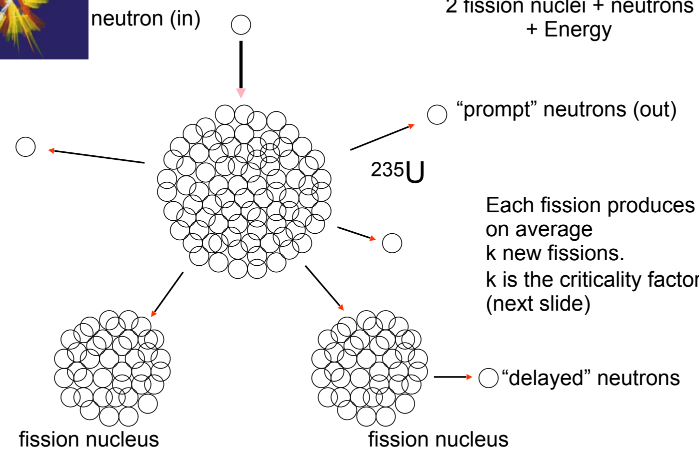
The enrichment technology makes use of centrifuges working on the minute mass difference of about 1.26% between ^{235}U and ^{238}U

Even very high-tech centrifuges have problems separating the two isotopes so the process must be repeated several times until the wanted enrichment is obtained.
Some ^{235}U will always remain in the left over Uranium mix.

Once you have the separation technology, there are no technical barriers to stop you continuing the separation process until you have reached bomb-grade Uranium, (example: Iran)

Fission:

neutron + ^{235}U ⟶ 2 fission nuclei + neutrons + Energy



Each fission produces on average k new fissions.
k is the criticality factor (next slide)

The Criticality Factor, **k**, of a Nuclear Reactor

k varies with the reactor geometry and the total mass of Uranium, higher mass means higher **k**

k varies with the average energy/speed of the neutrons, lower speed means higher **k** (*). Therefore the neutrons must be slowed down or “moderated” - for instance by water.

neutrons are absorbed by impurities like fission products, more impurities means more absorption and lower **k**

neutrons are also absorbed by control bars

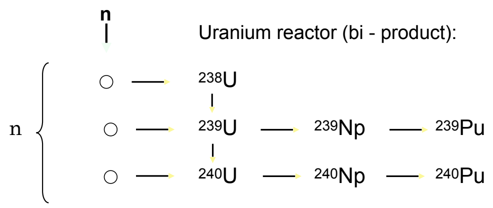
neutrons are also lost by absorption on Uranium238 (next slide)

A critical reactor **should** have **k exactly** equal to 1.

(*) a consequence of quantum mechanics

In a uranium reactor most of the uranium is non fissile, i.e. ^{238}U - even after enrichment.

Thus:



^{239}Pu is an excellent bomb material while ^{240}Pu is fertile/vaste

Chain reaction

Neutrons from uranium fissions hit other uranium nuclei and produce new fissions. When each fission leads to more than one new fission, k > 1, we have a chain reaction.

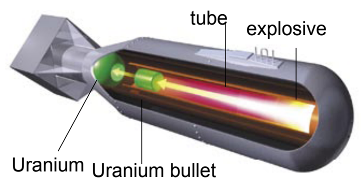
The number of fissions produced by one fission is given by the sum:

$$S = 1 + k + k^2 + k^3 + k^4 + \ldots\ldots$$

When $k < 1$, $S = 1/(1 - k)$, and a ”classical” reactor will stop.
When $k > 1$, S goes to infinity, and we have
a nuclear catastrophe (criticality accident) or a nuclear bomb

With k exactly equal to 1, we may have what we call a critical reactor.

Nuclear bomb, about 60 kg Uranium (or Plutonium)



The neutrons directly produced in the fission are prompt, and once produced they ”live” typically one milli-second inside the nuclear core. With k as low as 1.01 this will in one second lead to a multiplication by a factor 1.01^{1000}, or more than ten thousand, which is perfect for a bomb, but not so good for a reactor. (In fact a bomb has k ≈ 2 !!!)

Fortunately, 35% of the produced neutrons are coming from the fission products, (delayed neutrons), and thus increasing the average lifetime to about 0.1 s, giving a multiplication factor $1.01^{10} \approx 1.1$ (or 10%), which is a controllable rate of change for a reactor

Moderator:
The neutrons produced in Uranium fissions are ”fast”, and fast neutrons have a smaller probability than ”slow” or ”thermal” neutrons to produce another fission.
The fast neutrons are therefore slowed down or ”thermalized” by a moderator.

Control rods
are rods that are inserted in the reactor to absorb some of the neutrons and therefore reduce the probability for new fissions (i.e reducing the criticality k)

Also the fission products absorb neutrons and reduce the probability of new fissions and therefore k. This is why the reactor fuel in a critical reactor has to be reprocessed frequently.

Present Nuclear Reactors

Boiling water(*) reactors (BWR), is a light water reactor (LWR) and was the first reactor type, and which is still in use today

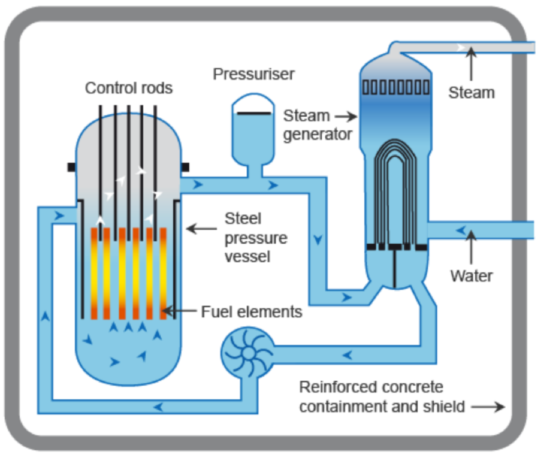
Pressurized water reactors (PWRs)
comprise the majority of all western nuclear power plants, and is another type of light water reactor

CANDU reactors (”Canada Deuterium Uranium”) reactors based on pressurized heavy water. (** comment)
All current Canadian reactors are of this type.

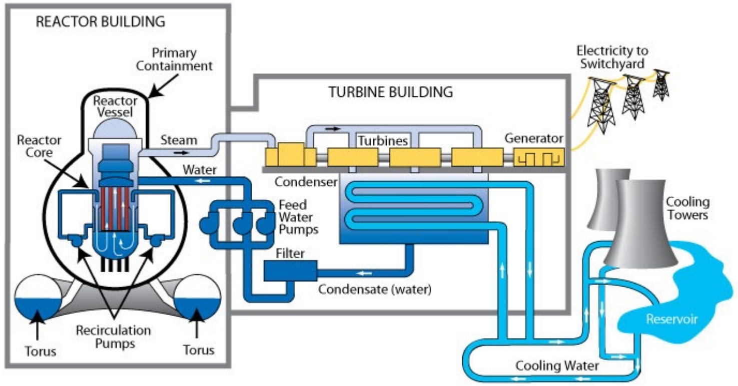
Liquid-Metal, Fast-Breeder Reactors mainly breeding Pu-239 from U-238 (Super Phoenix, France)

(*) Water act as coolant but is also an ideal self-regulating moderator: if the temperature increases the density and moderation decreases, leading to a decrease in k, **(i.e. a deterministic thermostat)**

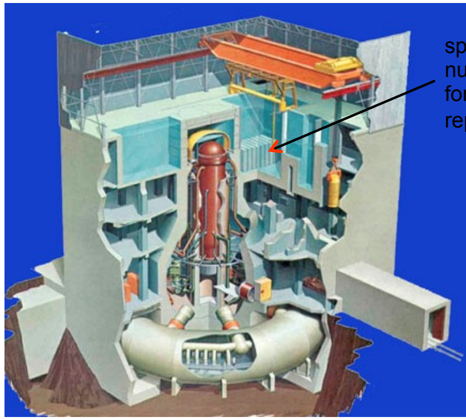
Schematic of a Boiling Water Reactor



a Boiling Water Reactor (BWR) (Fukushima)
(75 atm and 285 ^{o}C)

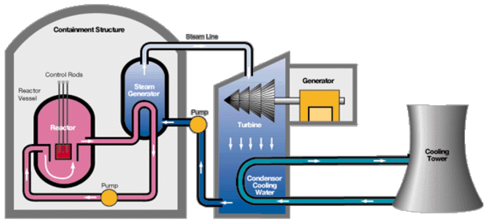


the Fukushima reactor



spent
nuclear fuel rods
for cooling before
reprocessing

Pressurized Water Reactor (PWR)

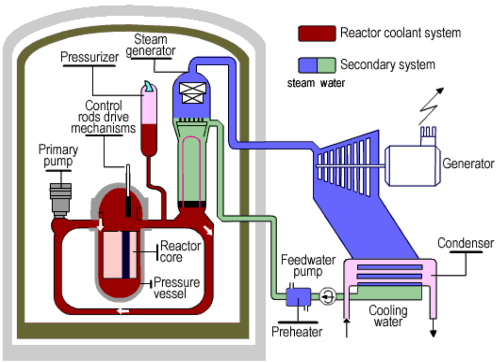


Superheated water is pumped under high pressure into the reactor core and act both as reactor coolant and moderator.
(Coolant at 153 atm and T_{out} = 583 K going to the steam generator)

PWR (EPR)

Olkiluoto, Finland (Areva + Siemens)
Planned start 2012 !!!!!!

EPR (Evolutionary or European pressurized water reactor)
see Olkiluoto web site at:
http://www.power-technology.com/projects/Olkiluoto/

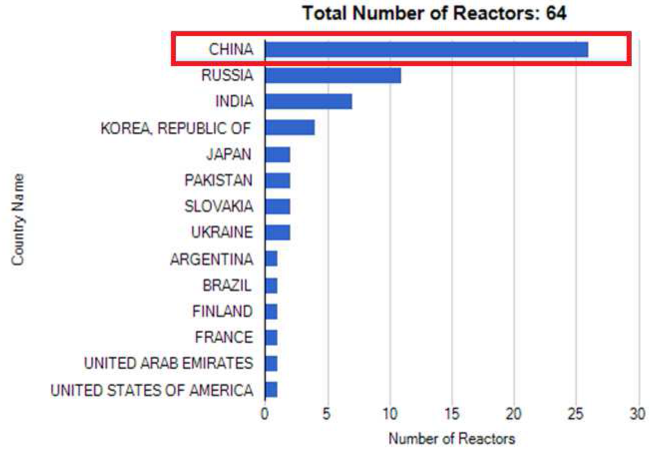


Thermal output:
4300 MW

Electrical output:
1600 MW

ie:
Efficiency: 37%

Nuclear Reactors under Construction



Problems with traditional fission reactors:

- Criticality accidents (public perception mostly)
  Long Lived Radioactive Waste
  Proliferation of Nuclear Bombs
- Limited Uranium Resources

A possible simultaneous solution to all these problems:

Nuclear Reactors based on the "Norwegian" element,
Thorium ^{232}Th, instead of Uranium (*)

(*) later in the presentation

Criticality with an external neutron source (ADS)

The criticality, k, depends on the amount of Uranium, the geometry of the reactor, the moderator(*) and control rods(*)

In a critical reactor k has to be maintained at $k = 1$
at all times !!!!
This is obtained by temperature dependent feedback
and control rods. (delayed neutrons) (*)

An Accelerator Driven System (ADS) based on Thorium
will be running at $k < 1$ at all times, and
criticality accidents can thus be avoided by design.
(explained later)

(*) See for inst. http://en.wikipedia.org/wiki/Nuclear_reactor_physics

Thorium reactors

There is 4 – 6 times more Thorium than Uranium in the Earth's crust, and Thorium is a much more efficient fuel than Uranium

Large amounts of accumulated experience in the use of Thorium and on the production of Thorium Fuel.

Still work to be done on commercialization of both critical reactors and accelerator driven systems based on the Th - ^{233}U cycle.

Also some problems in reprocessing need to be solved.

Options for thorium reactors

Use thorium blankets around reactors, to breed 233U and introduce 233U in fuel (n + 232Th ➔233Th ➔233Pa➔233U)

Continuously move the fuel out, such as to always have fresh fuel
- Pebble bed reactors (once through)
- Molten salt reactors (reprocessing on-line)
- Traveling wave reactor? (Encouraged by Bill Gates in Terra Power)

Providing an external neutron source – Accelerator Driven Systems (ADS)
this is the solution proposed by C. Rubbia at CERN in the 1990's and promoted by iThEC

Thorium is extracted as a 100% pure isotope and needs no enrichment.

But Thorium is not fissionable, but fertile:

n + ^{232}Th (1.4×10^{10} år) — ^{233}Th (22.3 min)

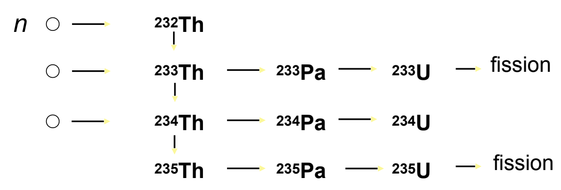
\ from fission or a proton accelerator + spallation medium (ADS)

| ^{233}Pa (27 days)

| ^{233}U (1.6×10^{5} years)

followed be extraction or direct burning of ^{233}U

Thorium reactor (main reaction chain)



Thorium Resources (< 80 US$ pr kg)

Country	Resource (`000 t Th)	%
Australia	420	17
US	400	16
Turkey	344	14
India	319	13
Venezuela	300	12
Brasil	221	9
Norway	132	5
Egypt	100	4
Russia	75	3
Greenland	54	2
Canada	44	2
South Africa	18	1
Others	33	1
Total	2460	100

61

An interesting comparison:

1 GW_e x year (= 9 TWh) requires:

0.7 tonnes of Thorium,
- 2 600 000 tonnes of coal,
2 000 000 tonnes of oil

One year electric consumption in Norway corresponds to about 9.7 tons Thorium.

which means that the Norwegian Thorium reserves could cover the Norwegian electricity consumption for about 13 000 years

62

Already a lot of accumulated experience on the use of Thorium and on industrial fuel fabrication,

so, why is not Thorium more widely used as a fuel ?

Things are changing !

63

The Pebble Bed Reactor is being reconsidered

The “old” Weinberg Molten Salt Reactor MSR) is being put back to life (i.e. China, India and Japan
+ intensive lobbying in the US)

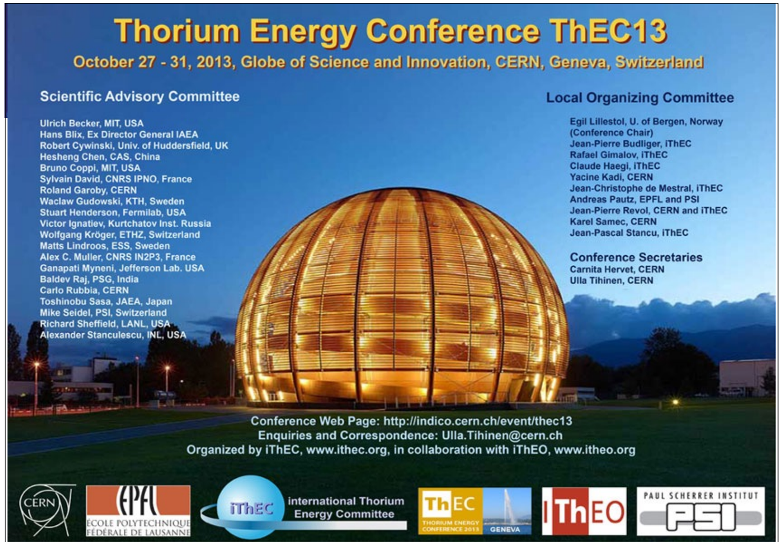
A new Accelerator Driven System (ADS) has been under study for several years

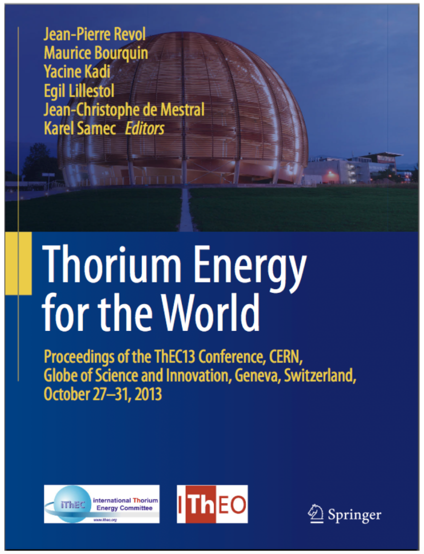
64

A new series of conferences on Thorium Energy was launched in 2010, with

ThEC10 in London
ThEC11 in New York
ThEC12 in Shanghai
ThEC13(*) at CERN in Geneva
(2014 TEAC-6 in Chicago)
ThEC15 in Mumbai

(*) next slide





The Thorium Energy Conference (ThEC13) gathered some of the world's leading experts on thorium technologies to review the possibility of destroying nuclear waste in the short term, and replacing the uranium fuel cycle in nuclear systems with the thorium fuel cycle in the long term.

The proceedings, which can be purchased from Amazon, is considered a reference work on Thorium Nuclear Technologies

The road to commercialization of critical reactors based on the Th - ^{233}U cycle is long and costly – not all the technical problems in reprocessing are solved, and only India and China (*) are r**eally** pushing ahead.

However, the Thorium cycle needed for an ADS is much simpler and could be developed fast !

(*) other countries now launching initiatives are Japan, Korea, Russia, USA, Belgium, and maybe also France

An ADS Thorium Reactor is robust.

Present day accelerator technology permits
the construction of a reactor for energy production
and elimination of waste

The reprocessing of fuel is rather simple
and proliferation resistant

69

Accelerator Driven Systems (ADS) based on Thorium

Accelerator Driven Systems (ADS) based on Thorium produce practically now radioactive waste, and can burn nuclear waste from Uranium reactors

ADS Thorium reactors can have a varying power output
and are the ideal **supplement to intermittent renewables**
They should be developed NOW !

70

Carlo Rubbia (CERN) (Nobel Laureate 1984)
Energy Amplifier Project (EA)

- uses Thorium in stead of Uranium

- driven by en accelerator (ADS)
(k < 1)

- produce very little radioactive waste

- can burn radioactive waste like
Plutonium (together with Thorium)
extracting an additional 30% energy

-can ¨not¨ be used for nuclear weapons

- Thorium reserves for thousands of years

71

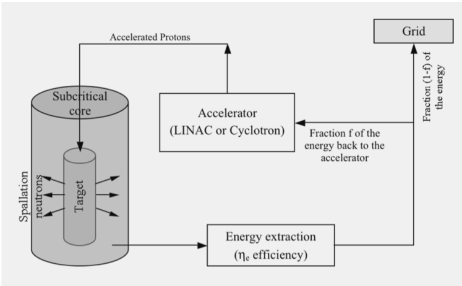
Carlo Rubbia at ThEC13

Unlike other energy sources, China's reserves of Thorium, may ensure the major domestic energetic supply for many centuries to come.
For instance the whole China's today electricity (3.2 Trillion kWh/ year) could be produced during ≈20'000 years by well optimized Th reactors and 8,9 million ton of Th, a by-product of the China's REE basic reserves.

72

ADS Principle:

- an accelerator produces a beam of 1 GeV protons
  a 1 GeV proton on a lead target produces ≈ 30 neutrons.
  each neutron makes 1/(1-k) new neutrons in ^{233}U,

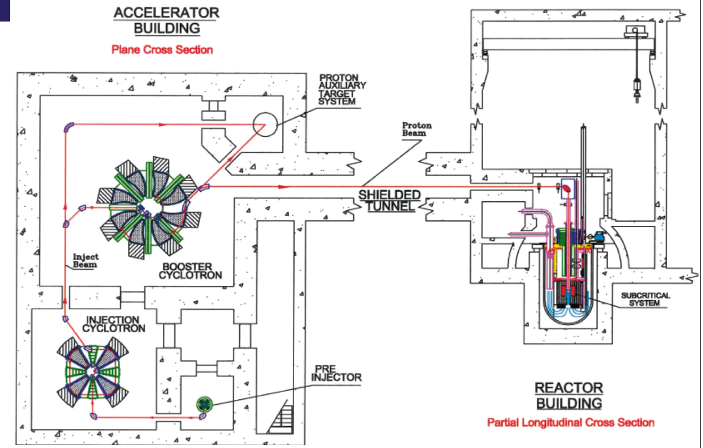


k is the criticality. For k = 0.98, one proton gives ~1500 neutrons, leading to ~750 fissions.

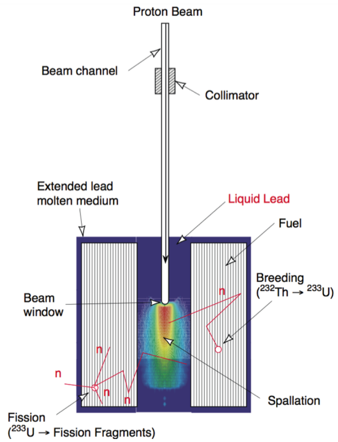
Each fission gives ~0.2 GeV energy, giving an energy amplification of 150

- i.e. a particle beam of 10 MW gives 1500MW$_{th}$ or 1.5 GW$_{th}$

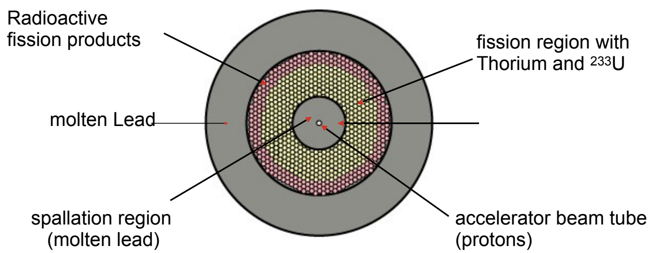
(From A. Kadi, CERN)

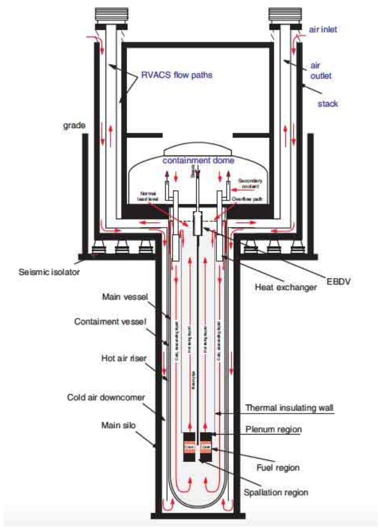


Schematic of the ADS core



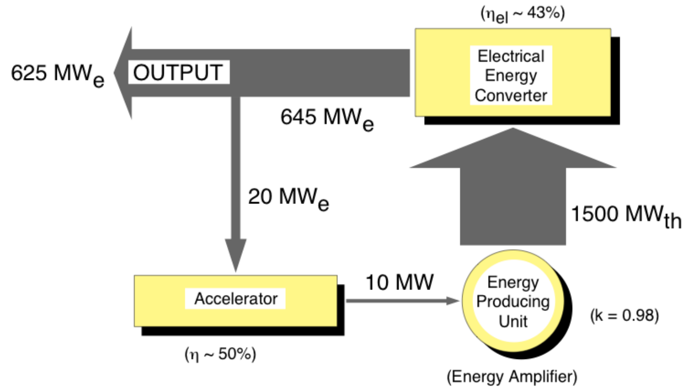
Reactor central part





C.R.'s drawing

From Carlo Rubbia: 1500 MW_{th} Reactor
(5 years per reprocessing)



Most important:

The output power is directly proportional with the accelerator current (or beam power), and this can be changed on seconds notice without changes in the criticality.

The system is therefore an ideal and may-be the only sustainable solution for back-up power in a mix with intermittent renewable electricity generation.

Massive renewable energy generation can hardly be successful without such a base load power

The fuel in an ADS Thorium reactor needs reprocessing only after 5 years and a refill of about 3 tons of Thorium oxide

Trans-uranium elements can be separated out in a rather simple pyro-electric process and put back into the reactor together with the most "inconvenient" fission products

At start:

27 tonnes ThO_2 and 3 tonnes U-235 (or Pu).

after some time of running the production and burning of ^{233}U will be in equilibrium

After 5 years and 1.5 GW continuous power: reprocessing, where

24 tons ThO_2 and 3 tons of produced U-233 is separated out and recycled together with 3 tons refill of ThO_2

(3 tons ThO_2 burnt)

and Could also just as well burn waste Plutonium

The Energy gain in the reactor calculated in very advanced simulation programs developed by Carlo Rubbias and his group at CERN

The programs and calculations verified in two large experiments at CERN, FEAT (*) and TARC, (1994 - 1995)

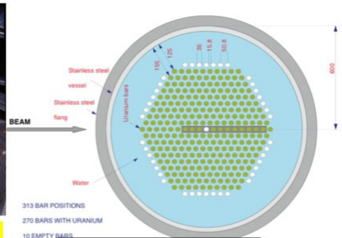
IMPORTANT:
The TARC has proved beyond doubt that an ADS can also be used to transmute radioactive fission elements form traditional nuclear reactors

(*) FEAT Experiment next two slides

FEAT, CERN

- The goal of the **First Energy Amplifier Test (FEAT)** at the CERN PS was to check the **basic concept of energy gain**, and **validate the innovative simulation** developed by C. Rubbia and his group.

3.62 t of natural uranium; k_{eff} ~ 0.9
(Spanish nuclear engineering school)
Juan Antonio Rubio



– Count fissions
– Measure temperature

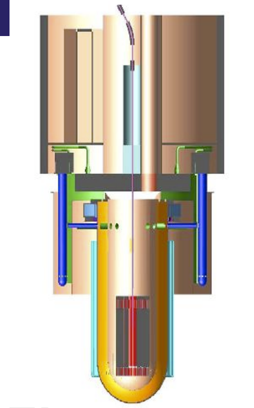
Participating groups and laboratories

CEN, Bordeaux-Gradignan, France
CIEMAT, Madrid, Spain
CSNSM, Orsay, France
CEDEX, Madrid, Spain
CERN, Genève, Switzerland
Dipartimento di Fisica e INFN, Università di Padova, Padova, Italy
INFN, Sezione di Genova, Genova, Italy
IPN, Orsay, France
ISN, Grenoble, France
Sincrotrone Trieste, Trieste, Italy
Universidad Autónoma de Madrid, Madrid, Spain
Universidad Politecnica de Madrid, Madrid, Spain
University of Athena, Athens, Greece
Université de Bâle, Bâle, Switzerland
University of Thessalonic, Thessalonique, Greece

My conclusion has been
and still is:

we should go for it !!!

http://www.thorea.org/publications/ThoreaReportFinal.pdf



Aker Solutions has taken part in the development since 2007 in collaboration with Carlo Rubbia, and has bought C.R.s world patent,.

They are now looking for partners to build the first prototype (outside Norway)

http://www.akersolutions.com/Internet/IndustriesAndServices/Nuclear+Services/NovelThoriumReactor.htm

November 2010:

Aker Solutions' Accelerator Driven Thorium Reactor has won the prestigious Energy Award at this year's IChemE (Institution of Chemical Engineers) Innovations and Excellence Awards.

The Energy Award recognizes the
best project or process to demonstrate innovation in renewable energy, alternative energy sources, efficient energy use or the development of energy production methods that reduce energy and water intensity.

However, in December 2010 Aker Solutions announced that most of their global process and construction activies now had been transferred to **Jacobs Engineering Group Inc.** (US)

Paul Scherrer Institute (PSI), Zürich, Sveits

has a 0.59 GeV, 3 mA, proton synchrotron,

a 1MW spallation target (lead-bismuth) with cooling systems and a cleaning tank was tested during 4 months continuous running (the MegaPie-experiment),

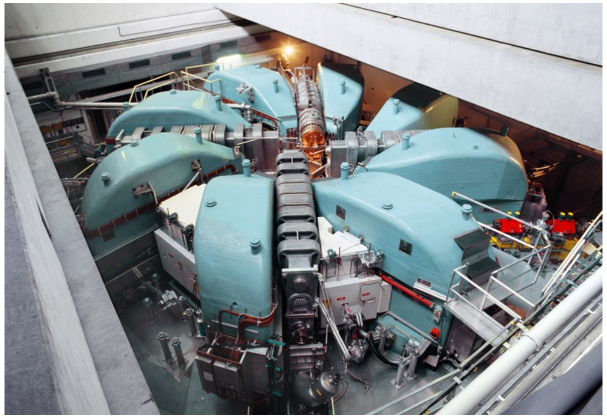
facilities for transport, reprocessing and production of nuclear material, and deposit facilities for radioactive waste,

infrastructure for a nuclear reactor.

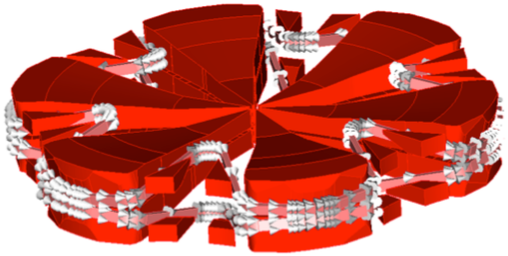
Needs a smaller reactor (maybe from a Russian nuclear submarine?

A demonstration system with 35 – 110 MW thermal power could be set up on a time scale of 5 – 8 years.
However, Switzerland is also contaminated with Radio-Phobia

The Paul Scherrer Inst, (PSI)'s Cyclotron (1974)
This could be used directly as a driver for an ADS prototype, and subsequently developed to a full scale ADS driver



New compact and powerful cyclotron is designed (AIMA)



And now we have Thor Energy
testing Thorium-Plutonium fuel in the Halden Reactor

http://www.smartplanet.com/blog/bulletin/as-thorium-tests-begin-in-norway-the-nuclear-industry-watches-closely/

and Norway's new government has declared that they want to create a new centre for sustainable energy (FME) based on Thorium —- but turned down by the National Assembly

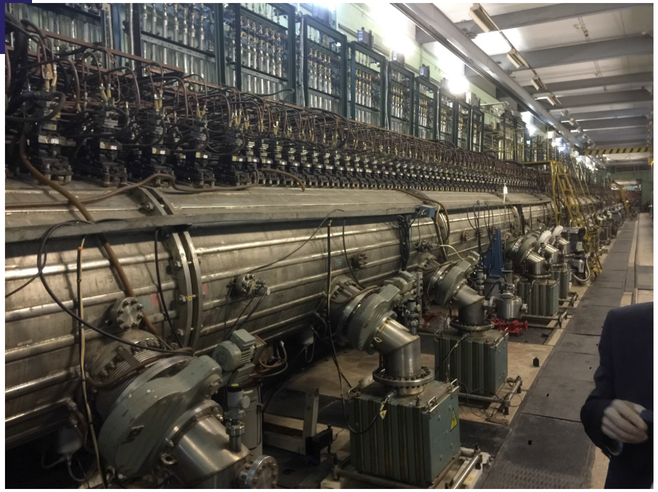
However, also an important fraction of the Norwegian Parliament is unaware of Norway's long-term negative economic outsights in addition to also being contaminated by radio-phobia,

so, for the moment the Government's "wish" is not accepted !

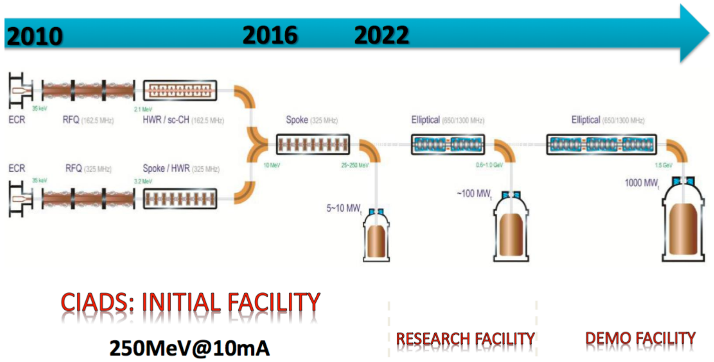
See my article in BT from July last year:
http://www.bt.no/meninger/kronikk/Thorium-kan-bli-den-nye-oljen-3151125.html#.U7ad8U0U91s

Thorium in a light water reactor:
Thor Energy (Norwegian company collaborating with Westinghouse) is now testing Thorium rods in the Halden reactor, and international recognised test reactor

iThEC @ Troitsk (Moscow)



China is going full speed:



250MeV@10mA
5-10MW

Rounding off:

https://www.youtube.com/watch?v=YUOP1JDIDS8&list=PLV5pFf44y8ozmIEQBObbt4_72betw40Ca