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Nuclear energy and decarbonated sustainable development

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Outline of the presentation

- Prelude : The « Big Picture »
- The case for Nuclear energy and global warming issues
  - *Decarbonation*
  - *Matter and space*
  - *Integration in an electric system*
- Structuring ideas on nuclear energy solutions: conditions for sustainability
- Integration of nuclear economy in a decarbonated economy
- Conclusions

Prelude : The Big Picture

The “Big Picture” (1)

- **Energy sources**
  - Solar
  - Wind
  - Mechanical
  - Hydro
  - Coal
  - Gaz
  - Nuclear
- **Energy vectors**
  - Electricity
  - Hydrogen
  - Heat
- **Energy usage**
  - Industry
  - Housing
  - Transport

The “Big Picture” (2)

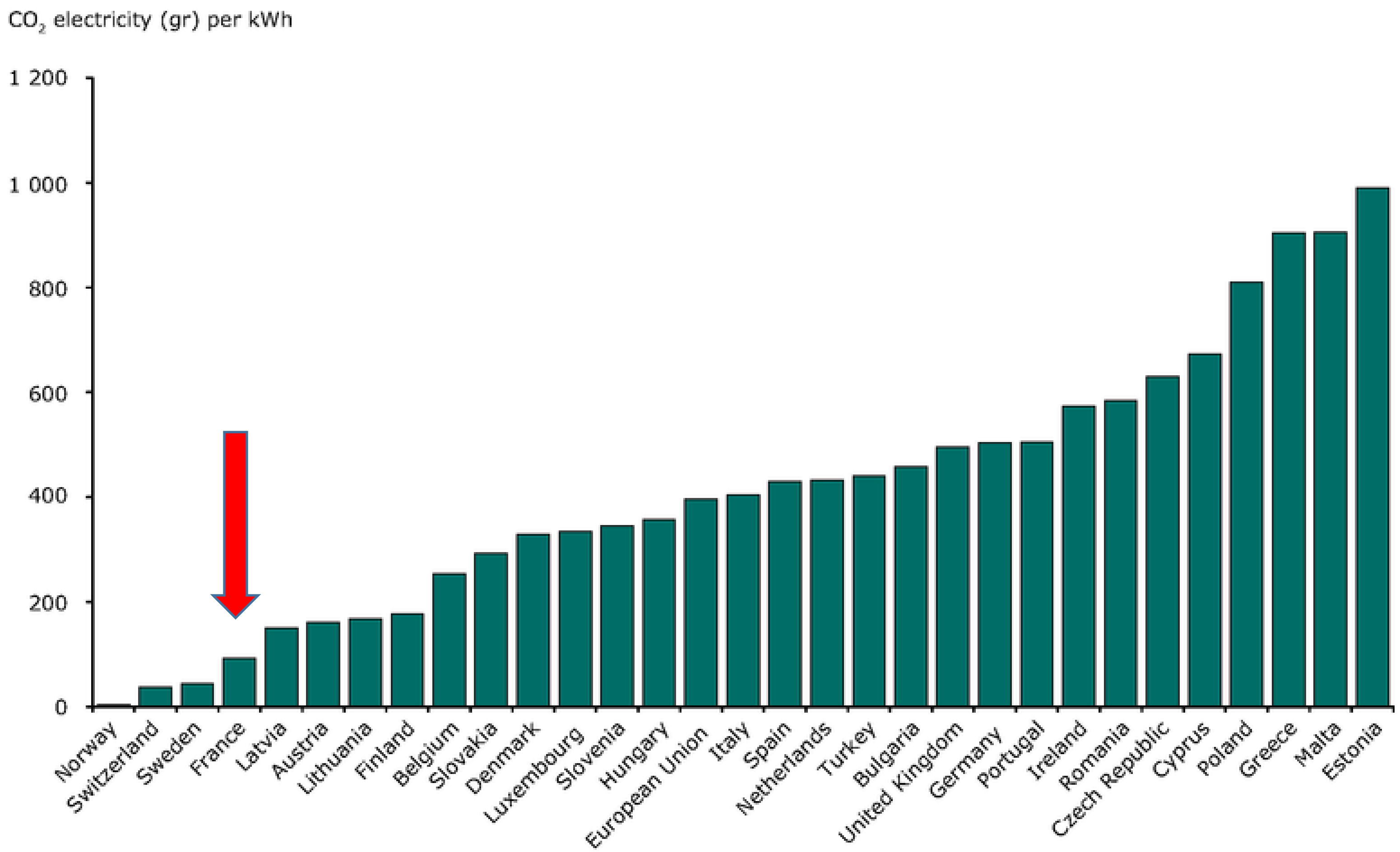
- **In order to produce, transport, and use energy we have to “make stuff”**
  - Energy production
  - Cables, pipes
  - Storage devices
  - Manufactured goods
- **In order to “make stuff,” you need:**
  - space ,
  - energy
  - raw materials
- **In order to “make stuff,” in a sustainable way**
  - Sustainability of resources
  - Impact on the environment
  - Contribution to global warming

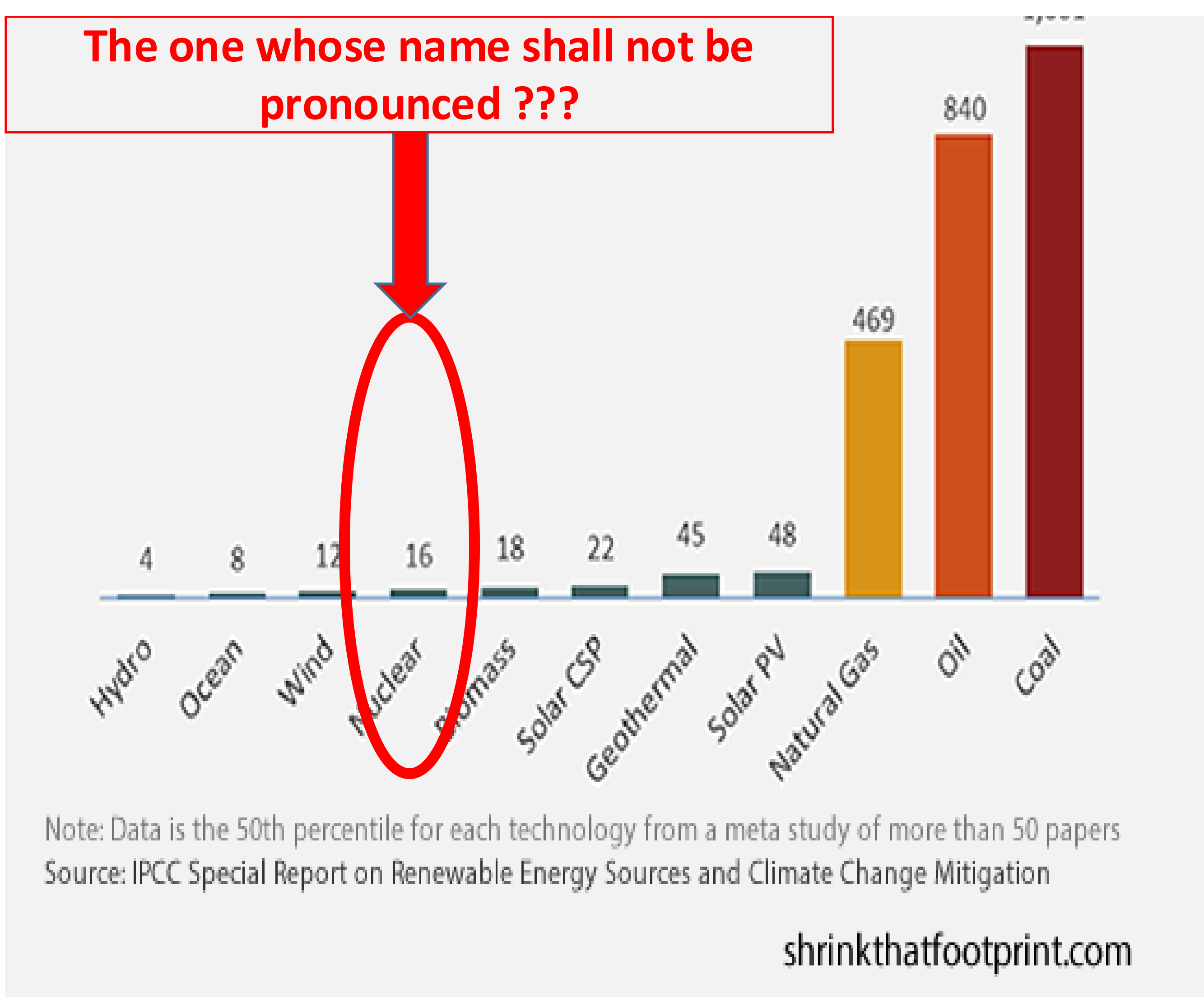
The “Big Picture” (3)

- Energy is the blood of economy
- Materials resources are the food of economy
- Energy resources are large CAPEX whatever is your choice, and it is a long term commitment
- Choosing a couple “energy production/Energy vector” must integrate
  - The needs
  - The initial conditions (what is the current situation?)
  - The boundary conditions (availability of resources…)
  - The objectives (economy, autonomy, …)

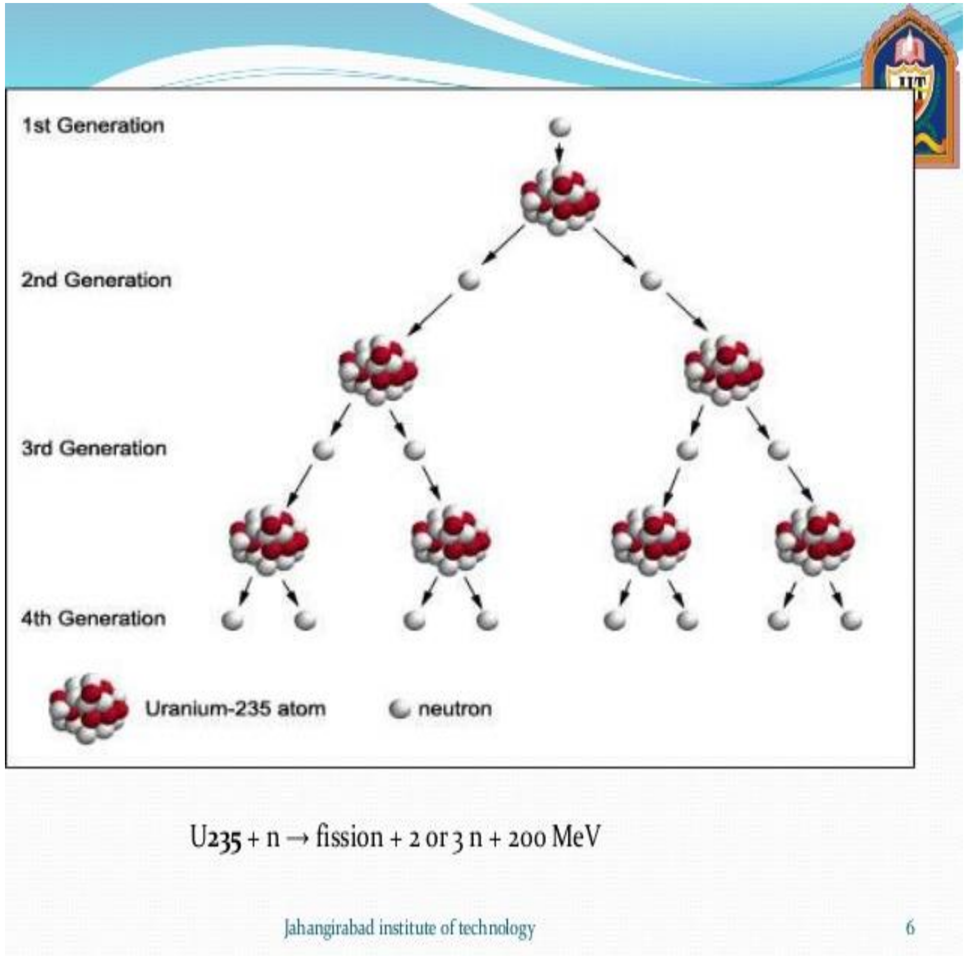
The case for Nuclear energy in a decarbonated economy

Carbon footprint for electricity per country




The one whose name shall not be pronounced ???
840
469
4
8
12
16
18
22
45
48
Hydro
Ocean
Wind
Nuclear
Solar CSP
Geothermal
Solar PV
Natural Gas
Oil
Coal
Note: Data is the 50th percentile for each technology from a meta study of more than 50 papers
Source: IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation
shrinkthatfootprint.com

Chain reaction + steam engine



Need to have a systemic approah of reactor /fuel/fuel cycle

<u>Neutron Economy</u>

Nature of the fuel (enrichment)

Géometry of assemblies

Moderators to slow down neutrons

Absorbtion of excess neutrons

<u>Evolution of elements</u>

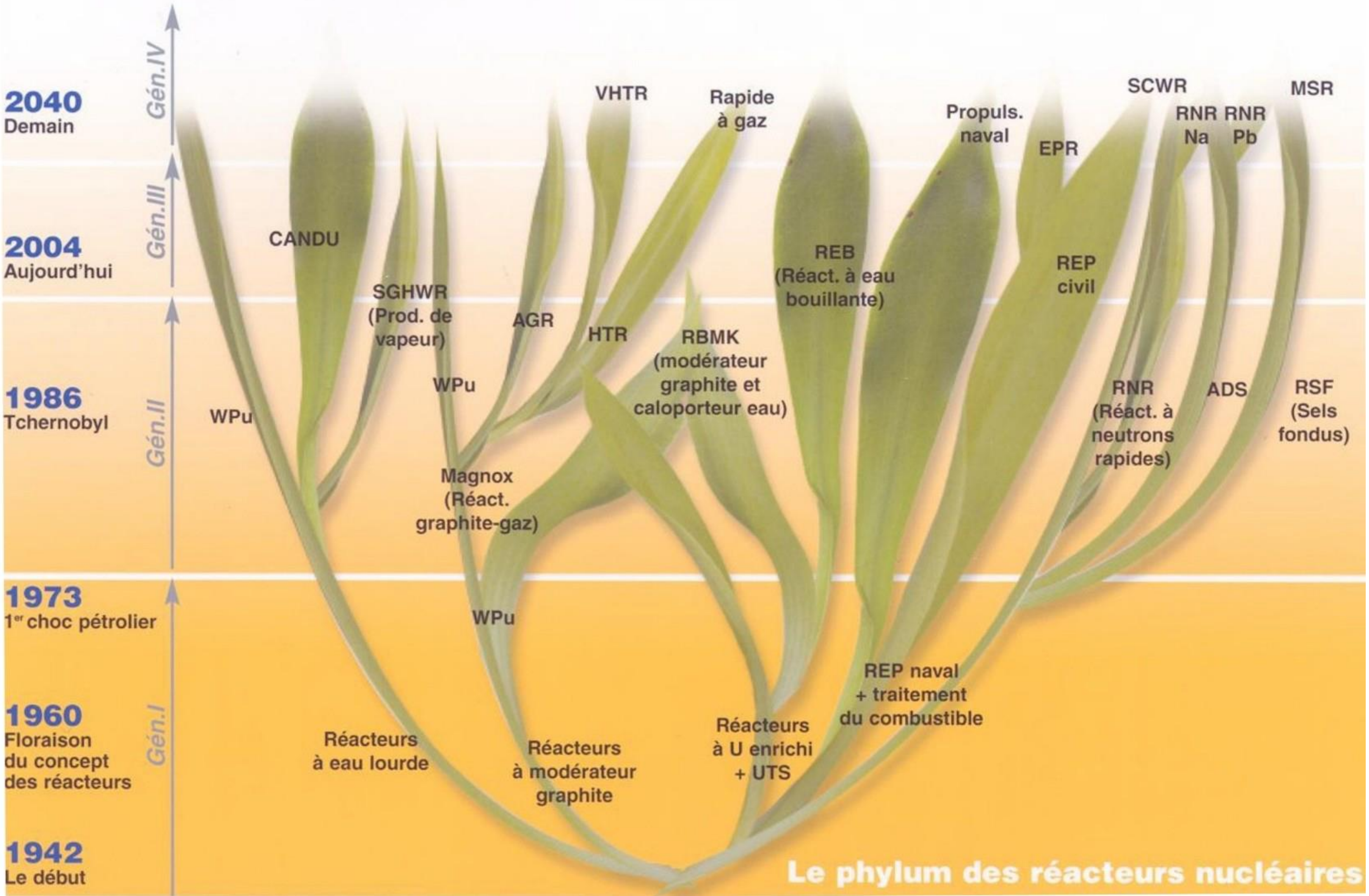
fission products

Actinides! Pu and minor actinides

<u>Heat Extraction</u>

Fluids

Circuits


2040
Demain
2004
Aujourd'hui
1986
Tchernobyl
1973
1er choc pétrolier
1960
Floraison du concept des réacteurs
1942
Le début
Gén.IV
Gén.III
Gén.II
Gén.I
CANDU
VHTR
Rapide à gaz
Propuls. naval
EPR
SCWR
RNR Na
RNR Pb
MSR
SGHWR (Prod. de vapeur)
AGR
HTR
RBMK (modérateur graphite et caloporteur eau)
REB (Réact. à eau bouillante)
REP civil
WPu
WPu
Magnox (Réact. graphite-gaz)
RNR (Réact. à neutrons rapides)
ADS
RSF (Sels fondus)
WPu
REP naval + traitement du combustible
Réacteurs à eau lourde
Réacteurs à modérateur graphite
Réacteurs à U enrichi + UTS
Le phylum des réacteurs nucléaires

H.G.RICKOVER, Admiral, US Atomic Energy Commission (1953)

An academic reactor or reactor plant almost always has the following basic characteristics: (1) It is simple. (2) It is small. (3) It is cheap. (4) It is light. (5) It can be built very quickly. (6) It is very flexible in purpose ("omnibus reactor"). (7) Very little development is required. It will use mostly "off-the-shelf" components. (8) The reactor is in the study phase. It is not being built now.

On the other hand, a practical reactor plant can be distinguished by the following characteristics: (1) It is being built now. (2) It is behind schedule. (3) It is requiring an immense amount of development on apparently trivial items. Corrosion, in particular, is a problem. (4) It is very expensive. (5) It takes a long time to build because of the engineering development problems. (6) It is large. (7) It is heavy. (8) It is complicated.

Technological Readyness level and decision strategies

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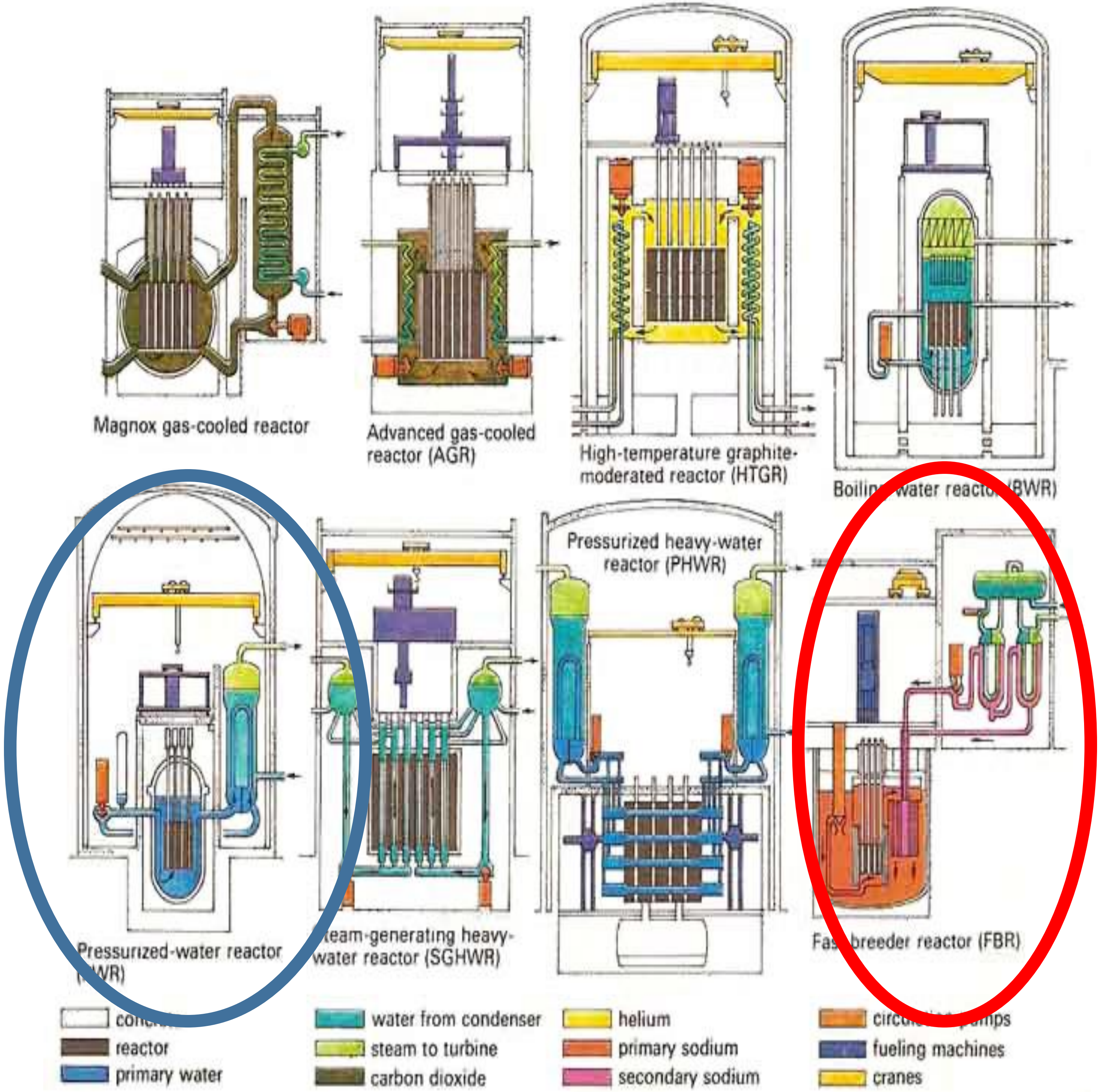
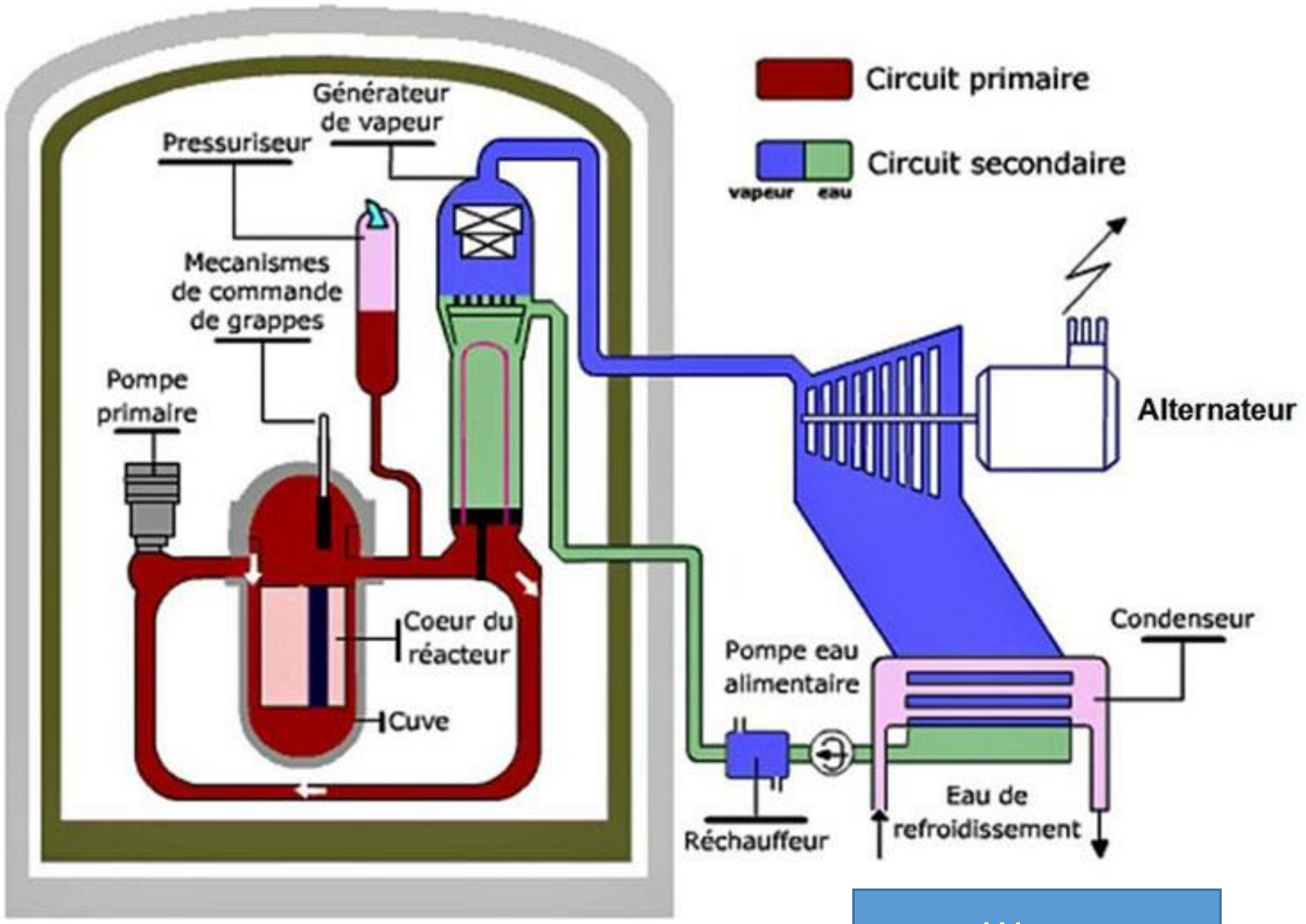
Available technologies	**Prototype technologies**	**Breakthrough technologies**
To be implemented NOW	To be industralised TOMORROW	Exploration and research To be impulsed
PWR reactors with U cycles, Water cooled SMR’s	Fast breeder reactors with U/Pu cycle	Fusions reactors Molten salt reactors

Pressurized Water Reactor (PWR)

Réacteur à Eau Pressurisée (REP)



FROM PAPER TO INDUSTRY



Water management or aerial cooling

Design : thermohydraulics et neutronics
Dimensionning and materials selection

Construction :
forge, welding…
civil engineering,

Operation
Fuel fabrication, cladding,
Component replacement…
Corrosion, Ageing under irradiation

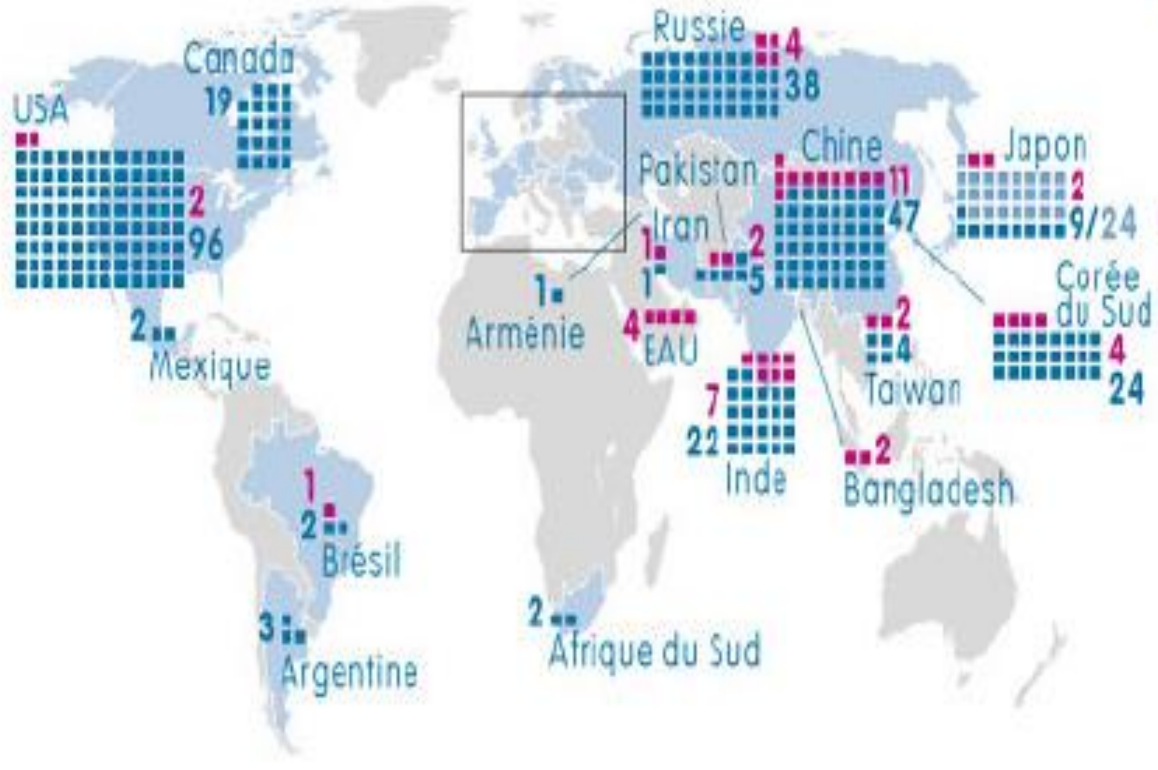
Les centrales nucléaires dans le monde

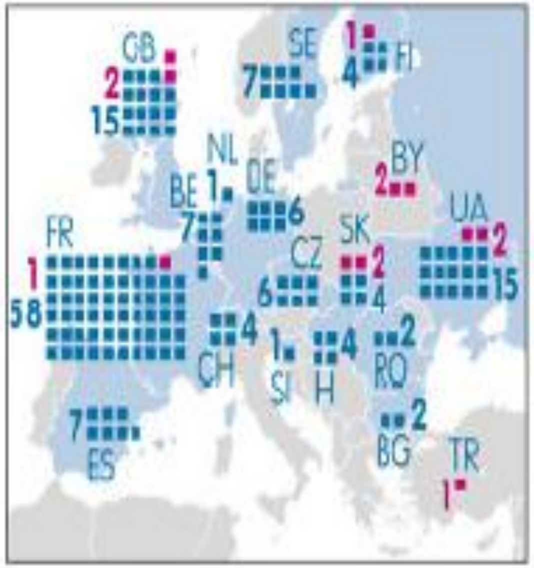
Etat: 31.12.2019

■ Centrales nucléaires en service: 442
■ dont actuellement en arrêt: 24
Puissance totale: env. 391'300 MW

Part dans la production mondiale d'électricité en 2019: ca.10%

■ Centrales nucléaires en constr.: 53
Puissance totale: env. 55'400 MW





Source: Forum nucléaire suisse

energienucleaire.ch

Matter and space

Space needed for various energy resources

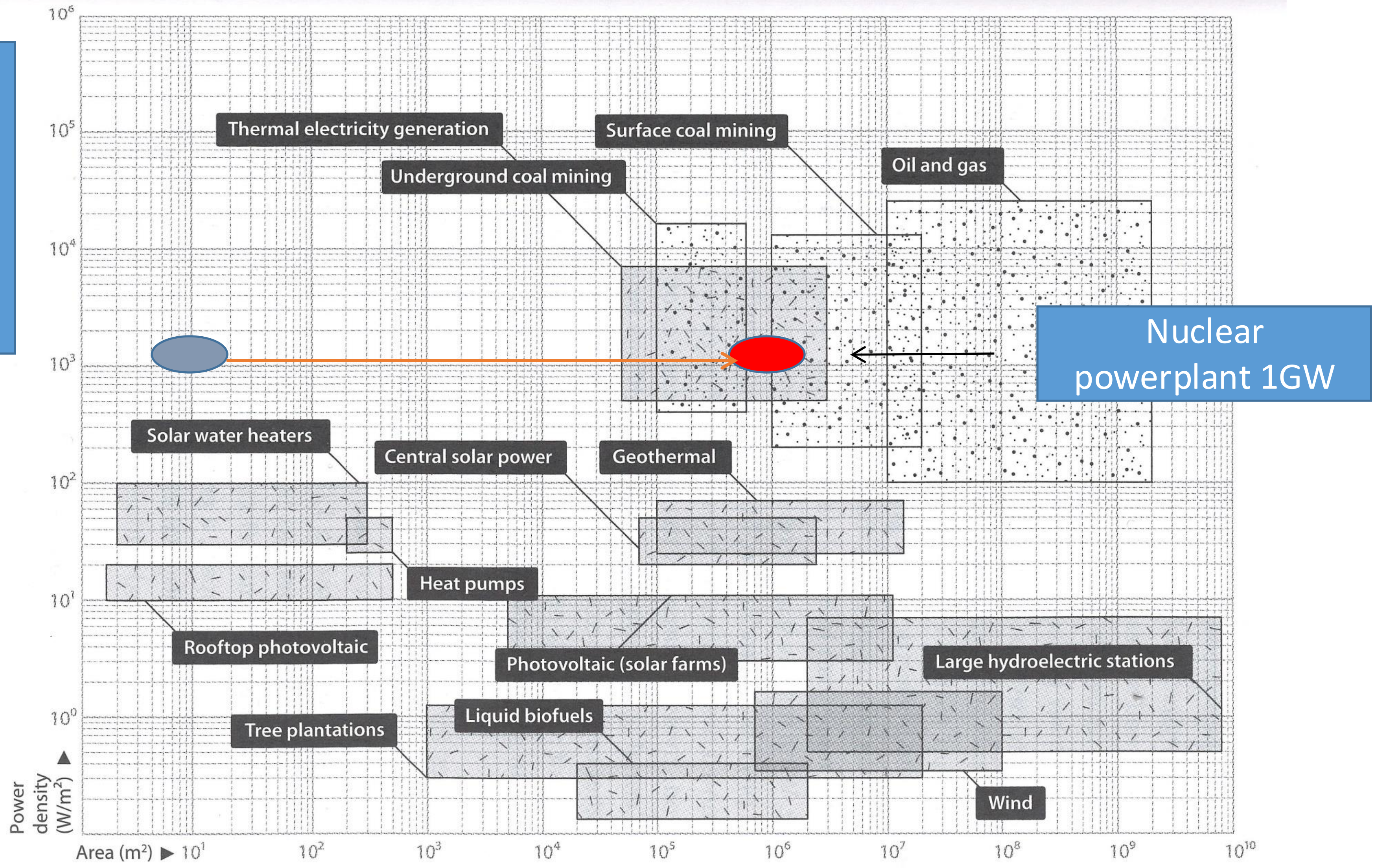


Figure 7.3

Power densities of fossil energy conversions and renewable energies. Carl De Torres Graphic Design. *Notes:* Area (m^2) is displayed on the *x*-axis, power density (W/m^2) on the *y*-axis. Figures were calculated for liquid biofuels, tree plantations, wind energy, large hydroelectric stations, PV-based sources (solar farms), rooftop PV arrays, central solar power, geothermal power, heat pumps, solar water heaters, oil and gas operations, surface coal mining, thermal electricity generation, and underground coal mining.

Comparison production consommation: Possible need for grids…

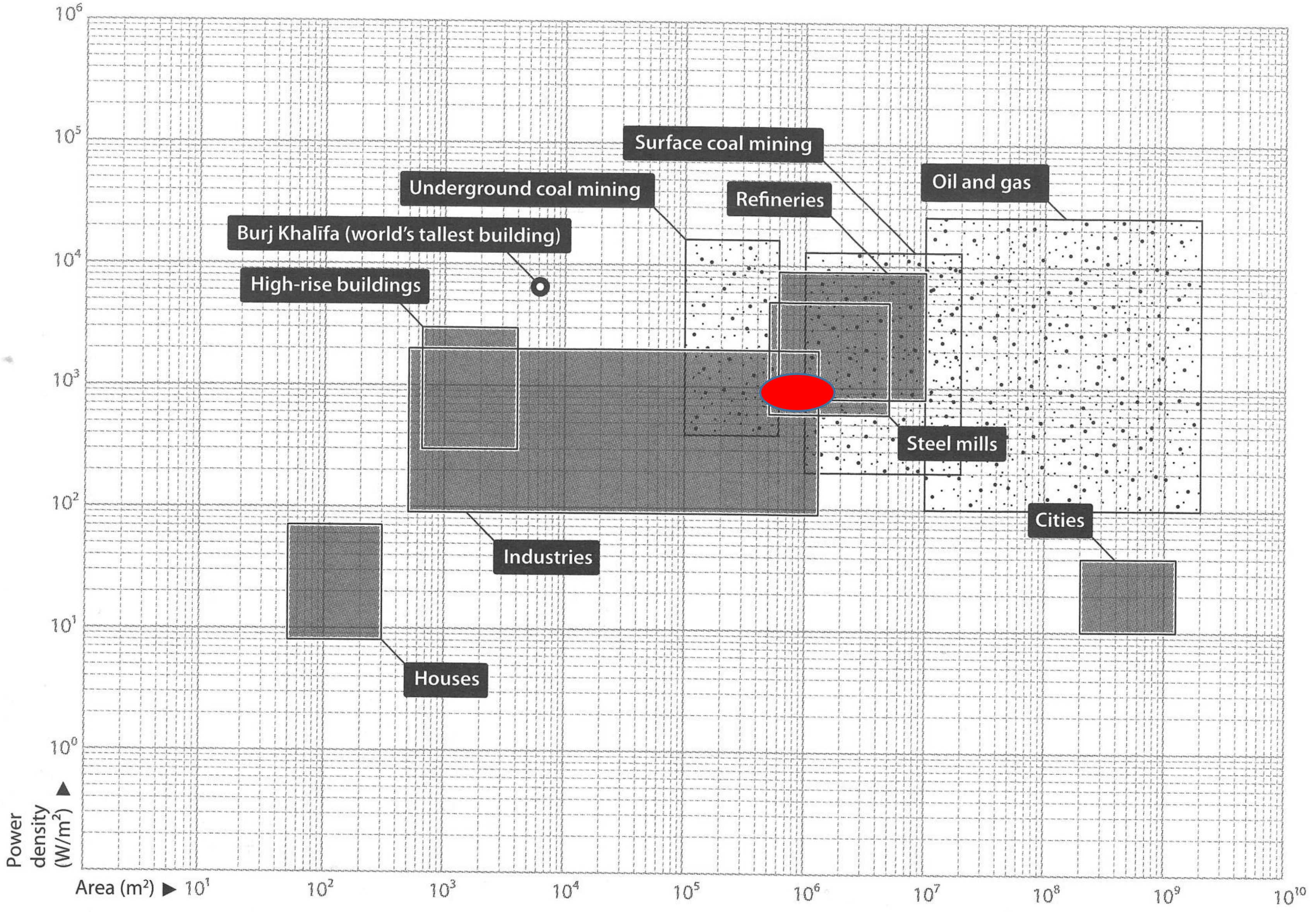


Figure 7.4

Power densities of fossil fuel energetics and modern energy use. Carl De Torres Graphic Design.

Comparison between renewables and nuclear…

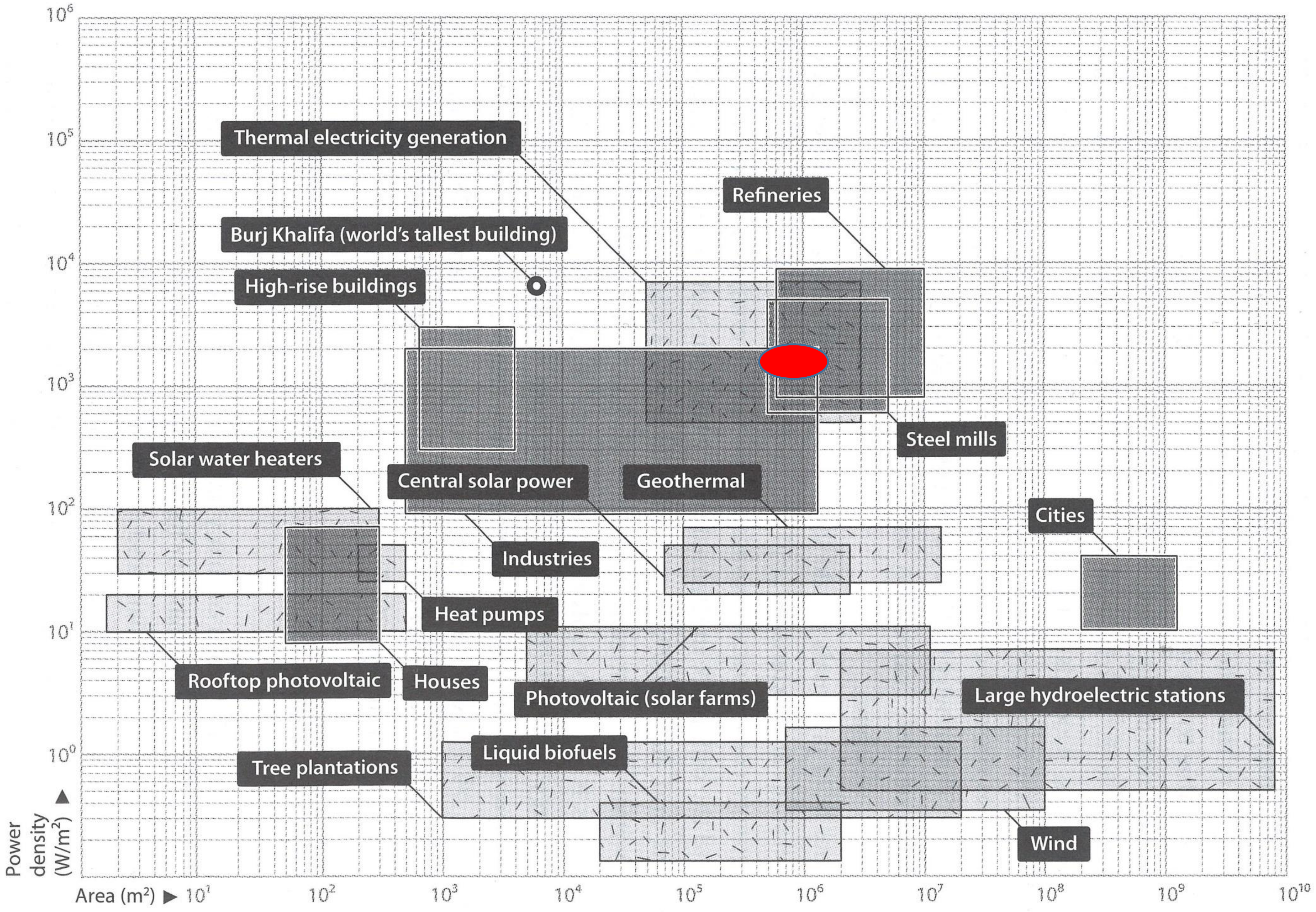
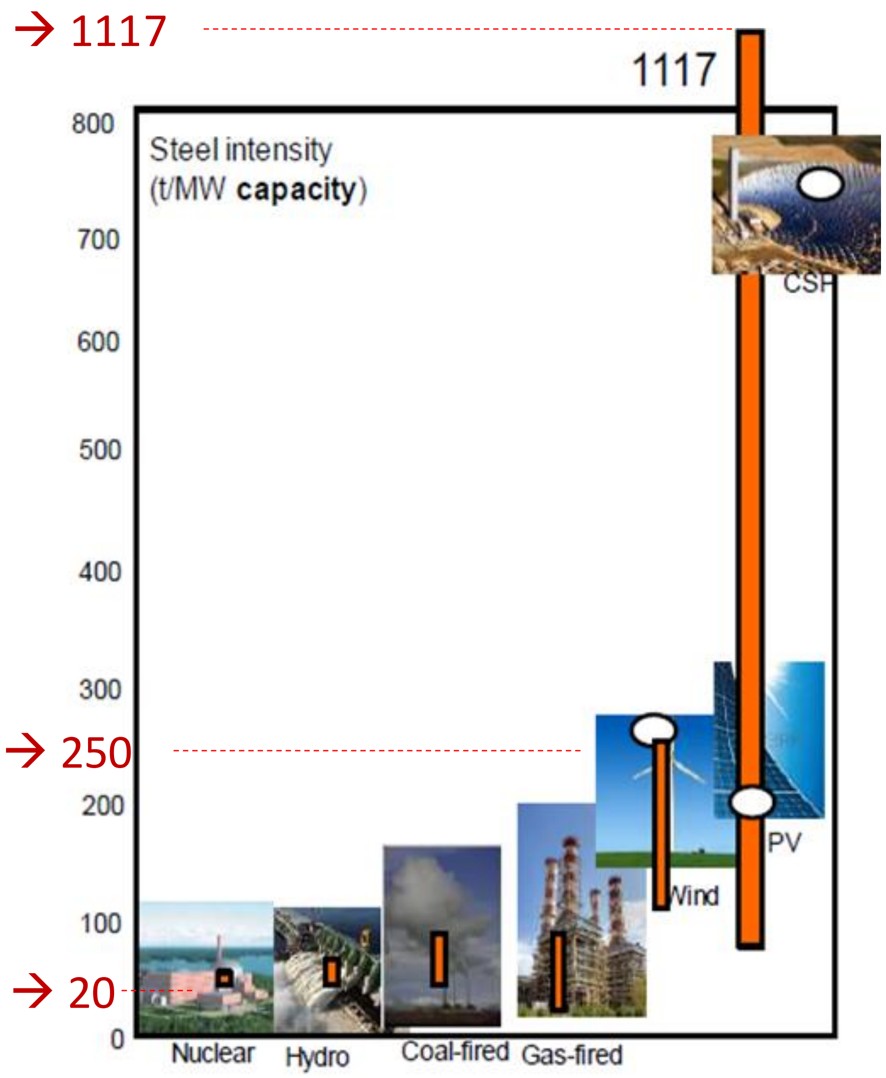


Figure 7.5

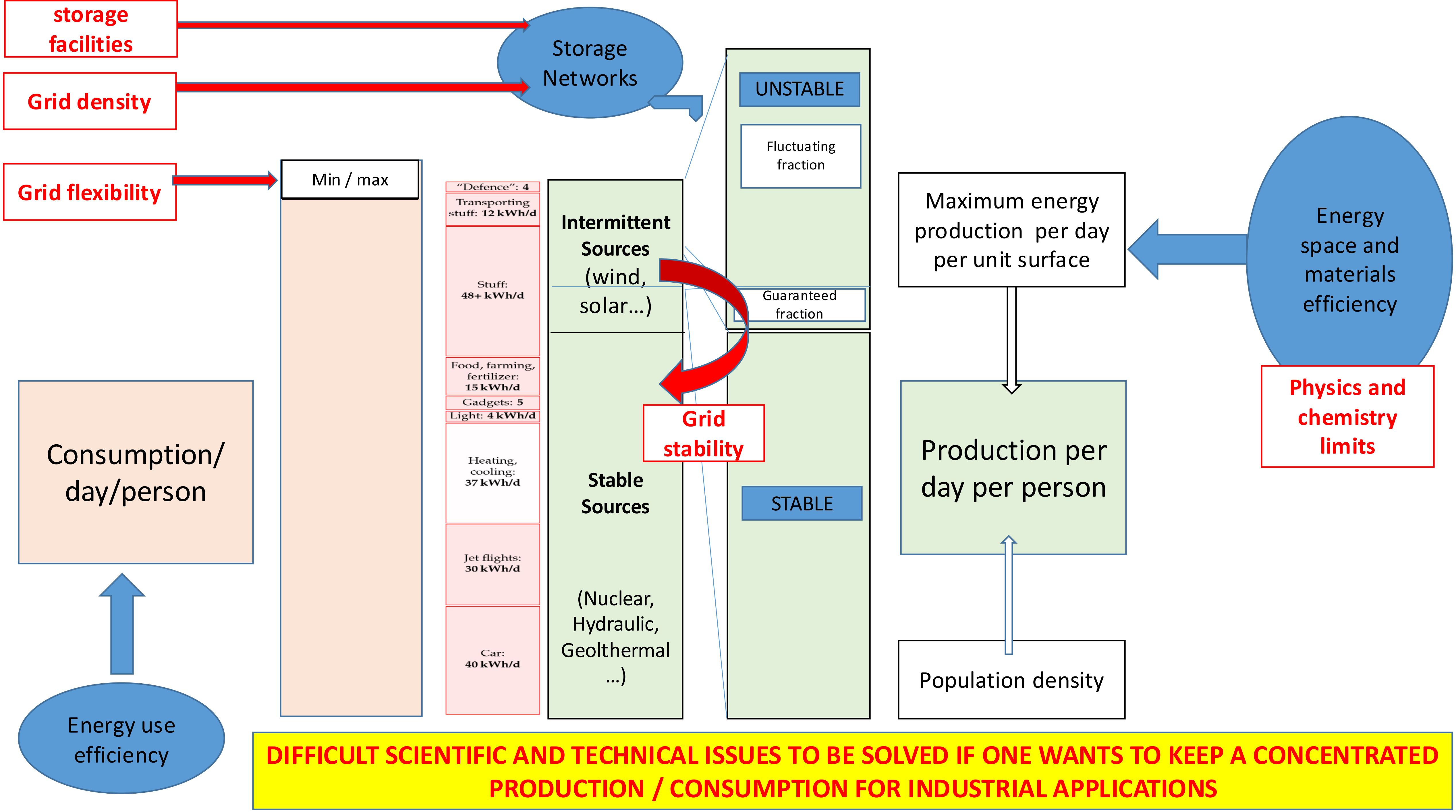
Power densities of renewable energetics and modern energy use. Carl De Torres Graphic Design.

Materials intensity



Wind turbine generation 6 MW with rotor >150m
1500 t of steel -
permanents magnets with rare earth
…
Nd, Dy, Sm, Gd, or Pr

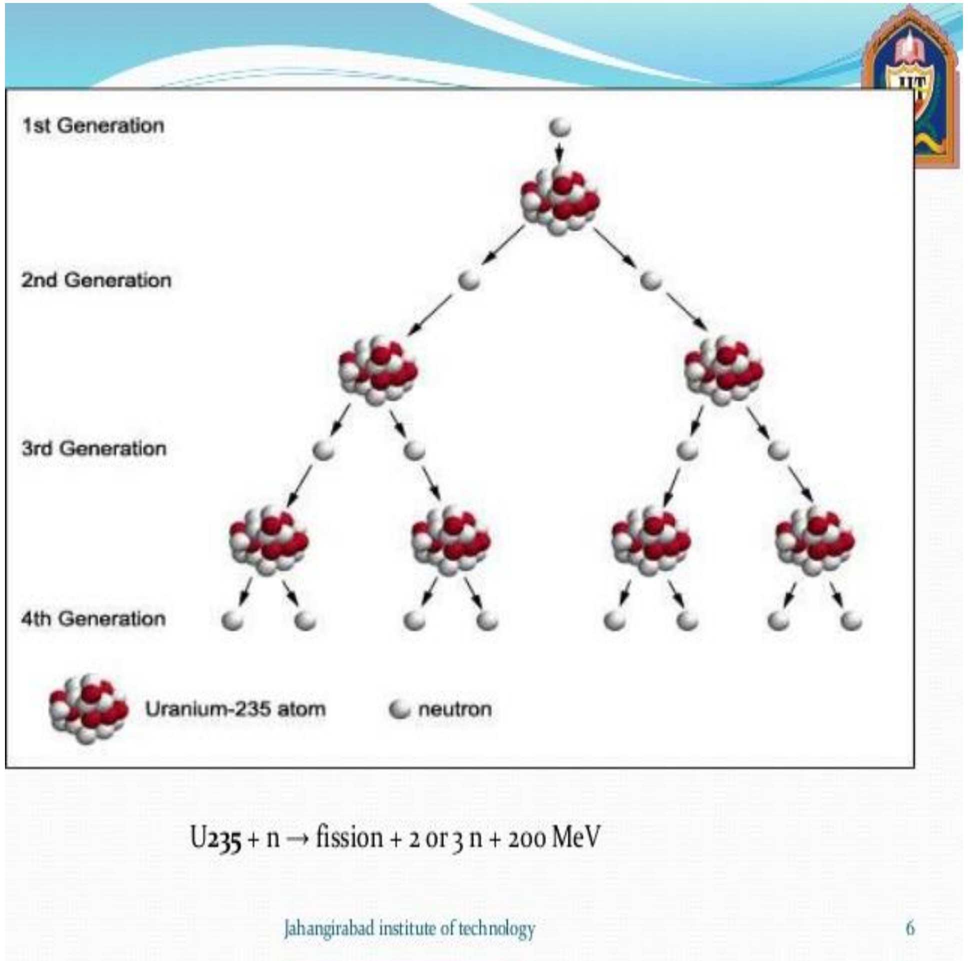
Integration in a system…



storage facilities
Grid density
Grid flexibility
Storage Networks
Min / max
"Defence": 4
Transporting stuff: 12 kWh/d
Stuff: 48+ kWh/d
Food, farming, fertilizer: 15 kWh/d
Gadgets: 5
Light: 4 kWh/d
Heating, cooling: 37 kWh/d
Jet flights: 30 kWh/d
Car: 40 kWh/d
Intermittent Sources (wind, solar…)
Stable Sources
(Nuclear, Hydraulic, Geolthermal …)
UNSTABLE
Fluctuating fraction
Guaranteed fraction
Grid stability
STABLE
Maximum energy production per day per unit surface
Production per day per person
Population density
Energy space and materials efficiency
Physics and chemistry limits
Consumption/ day/person
Energy use efficiency
DIFFICULT SCIENTIFIC AND TECHNICAL ISSUES TO BE SOLVED IF ONE WANTS TO KEEP A CONCENTRATED PRODUCTION / CONSUMPTION FOR INDUSTRIAL APPLICATIONS

Structuring ideas on the role of Nuclear energy: conditions for sustainability

Chain reaction + steam engine



<u>Neutron Economy</u>

Nature of the fuel (enrichment)

Géometry of assemblies

Moderators to slow down neutrons

Absorbtion of excess neutrons

<u>Evolution of elements</u>

fission products

Actinides! Pu and minor actinides

<u>Heat Extraction</u>

Fluids

Circuits

« Neutron Grocery Shop »

« Steam Engine»

FUEL

WASTE

ELECTRICITY and HEAT GENERATION

How can we secure the resource?
How can we limit the waste?

The wisdom of Fermi

closing the fuel cycle: transform the waste into resource

Key ideas on nuclear physics (1)

- Fissile element: can undergo nuclear fission by neutron bombardmnt of any energy : U235 (0,7% of natural uranium)
- Fertile element: can become fissile by capturing a neutron (Pu created by U238, U233 created by Thorium)

- Neutron created by fission are « fast » and can’t break efficiently U235 (cross section) . In order to be efficient, they have to be slowed down (water, gaz as a moderator) BUT the absorption increases, creating long live waste (Actinides), and creating Pu239 and Pu240 (non fissile isotope)
- The fissile Pu 239 can be separated and reincorporated in Fuel (MOX)

Key ideas on nuclear physics (2)

- If the neutrons are not slowed down (Fast Neutrons) , Pu239 is NOT degraded, U238 generate Pu239

- The fuel made of Pu239 and U238 (which makes use of the otherwise useless U238) can be used in a breeder mode (create more Pu) or un a isogenerator mode (consume as much Pu as it produces)

- In order to keep the neutron fast, they have to « bounce back » on heavy atomes : water is excluded, molten lead and molten Sodium can be efficient coolants keepin the energy of neutrons high

- The idea of fast neutron reactors dates from Fermi, as well as the construction of the first atomic reactor!

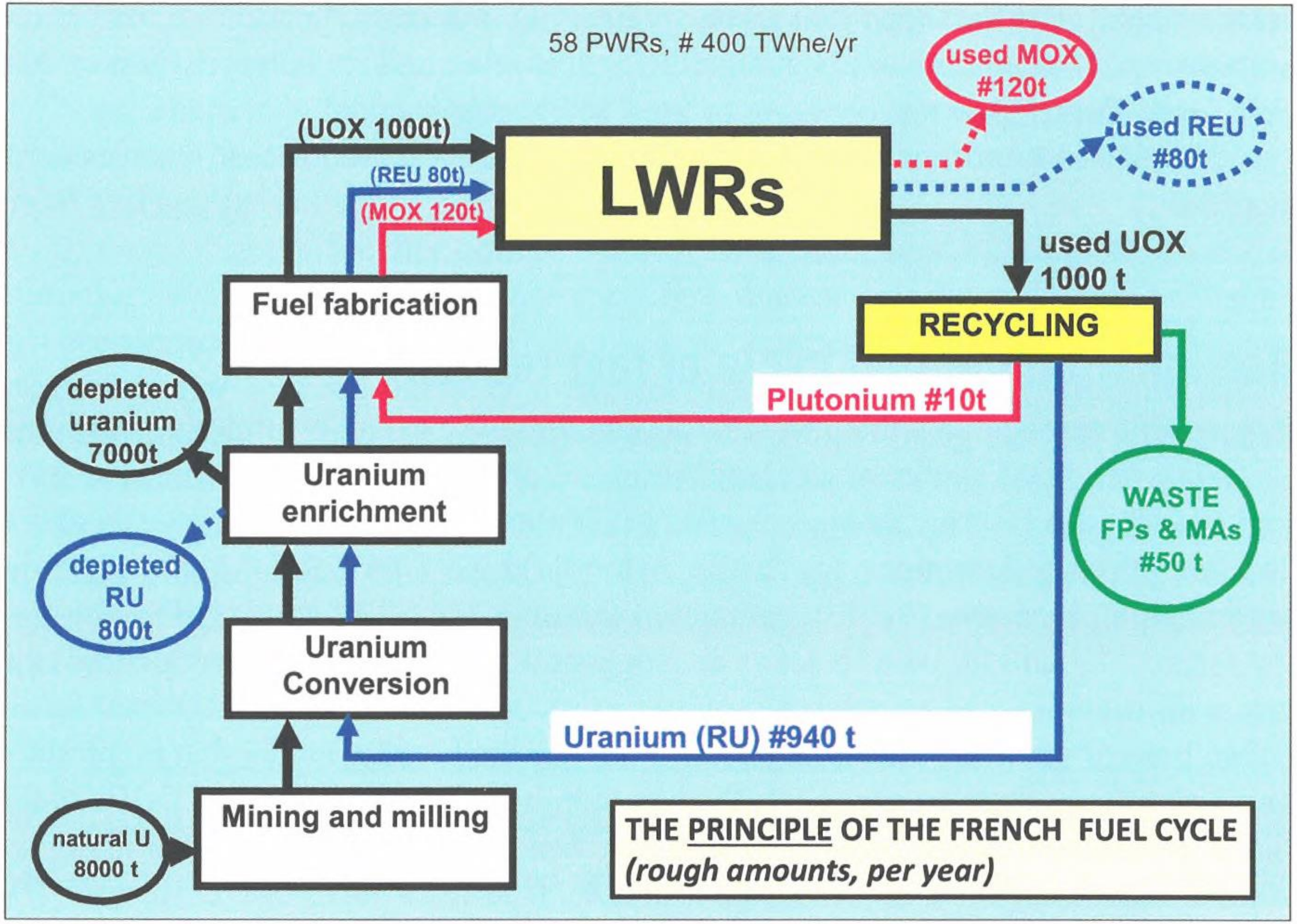
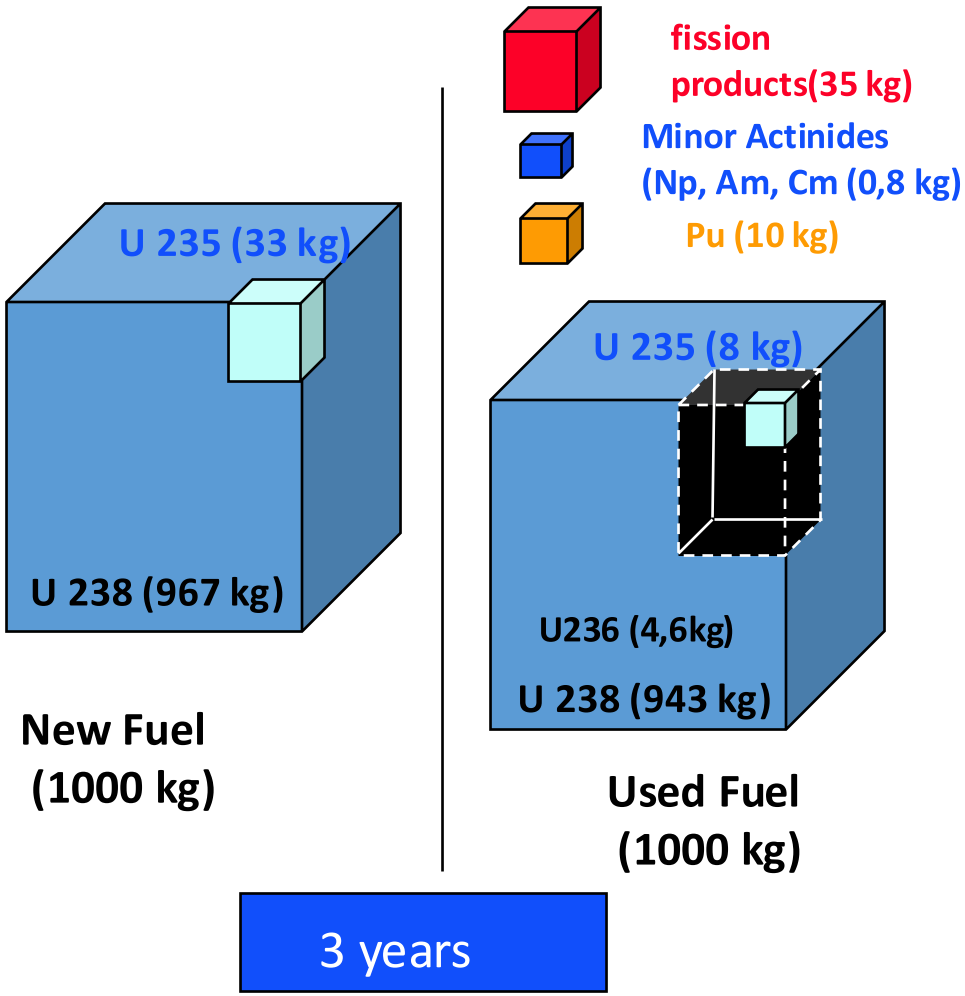
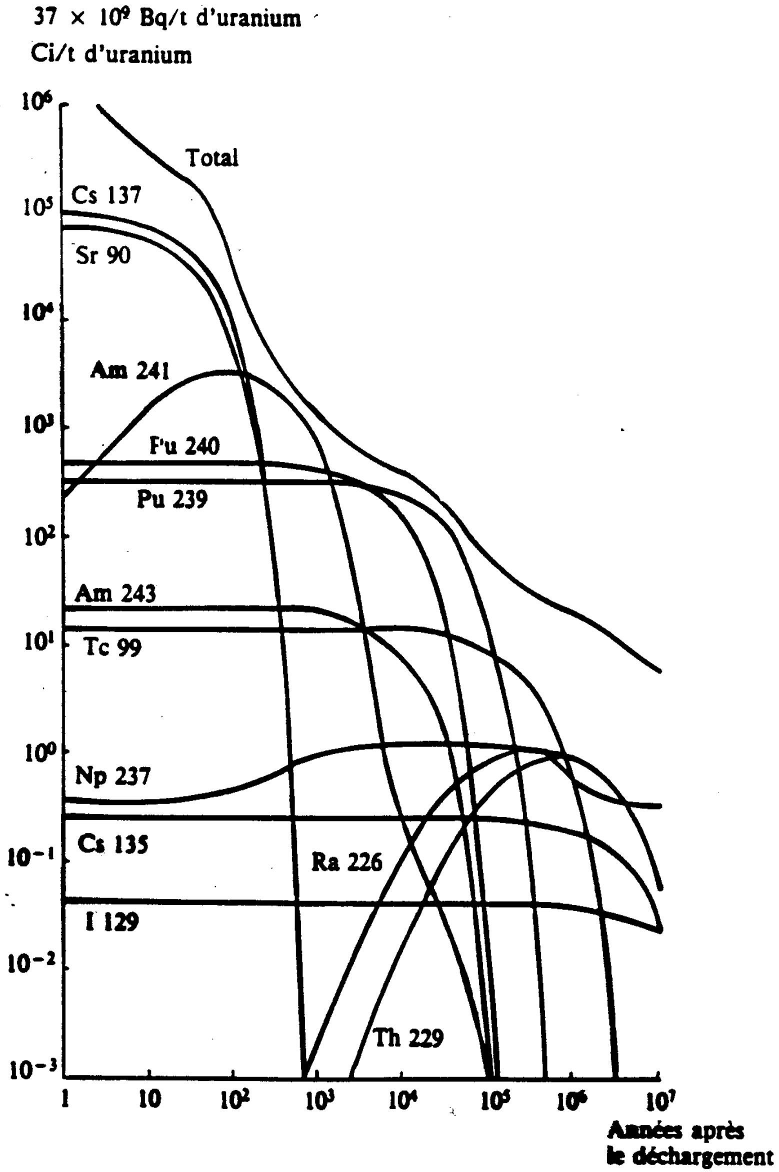


FIG. 1

Fuel cycle of French reactors with reprocessing activities.

The High activity long life nuclear waste





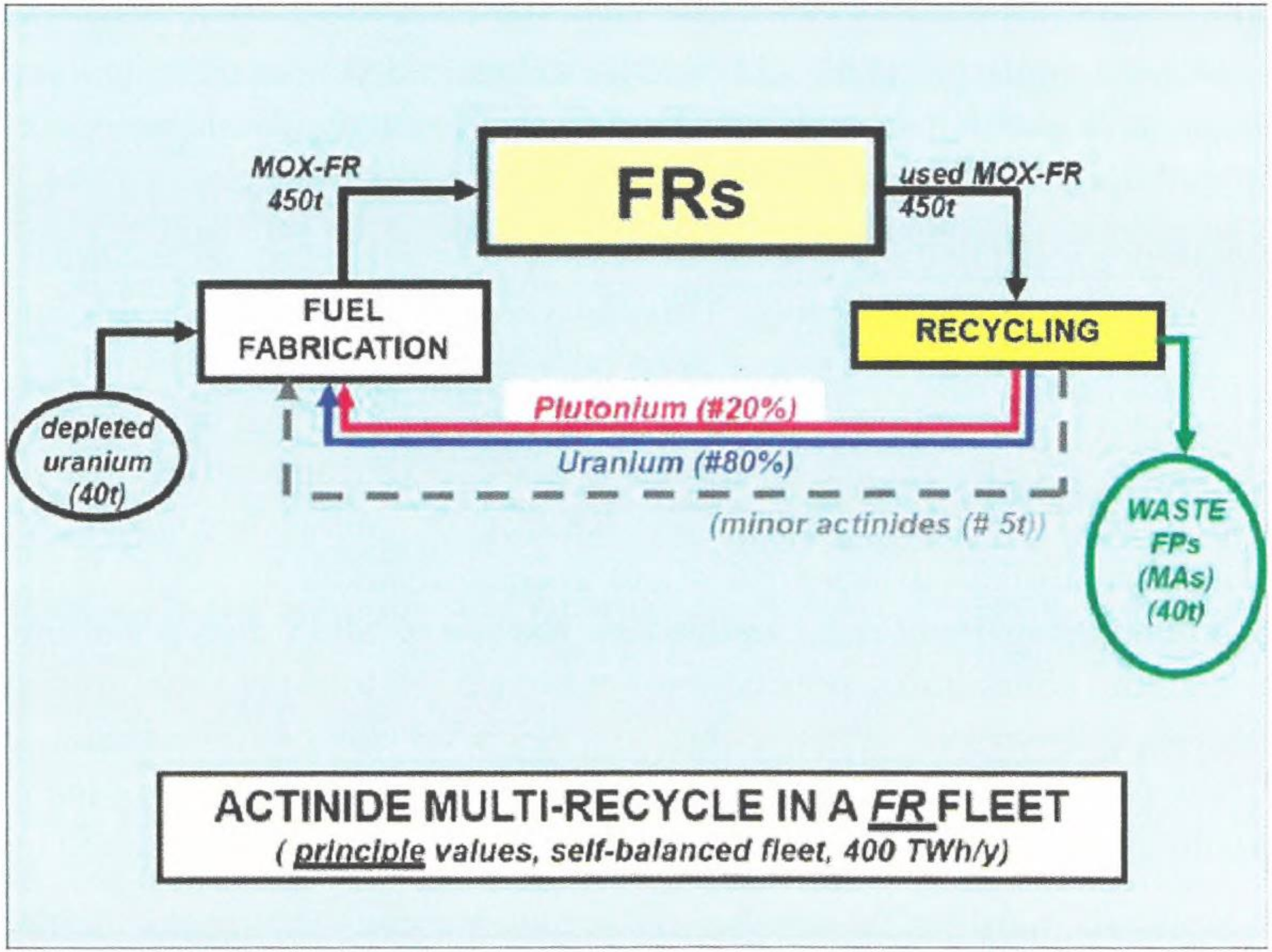
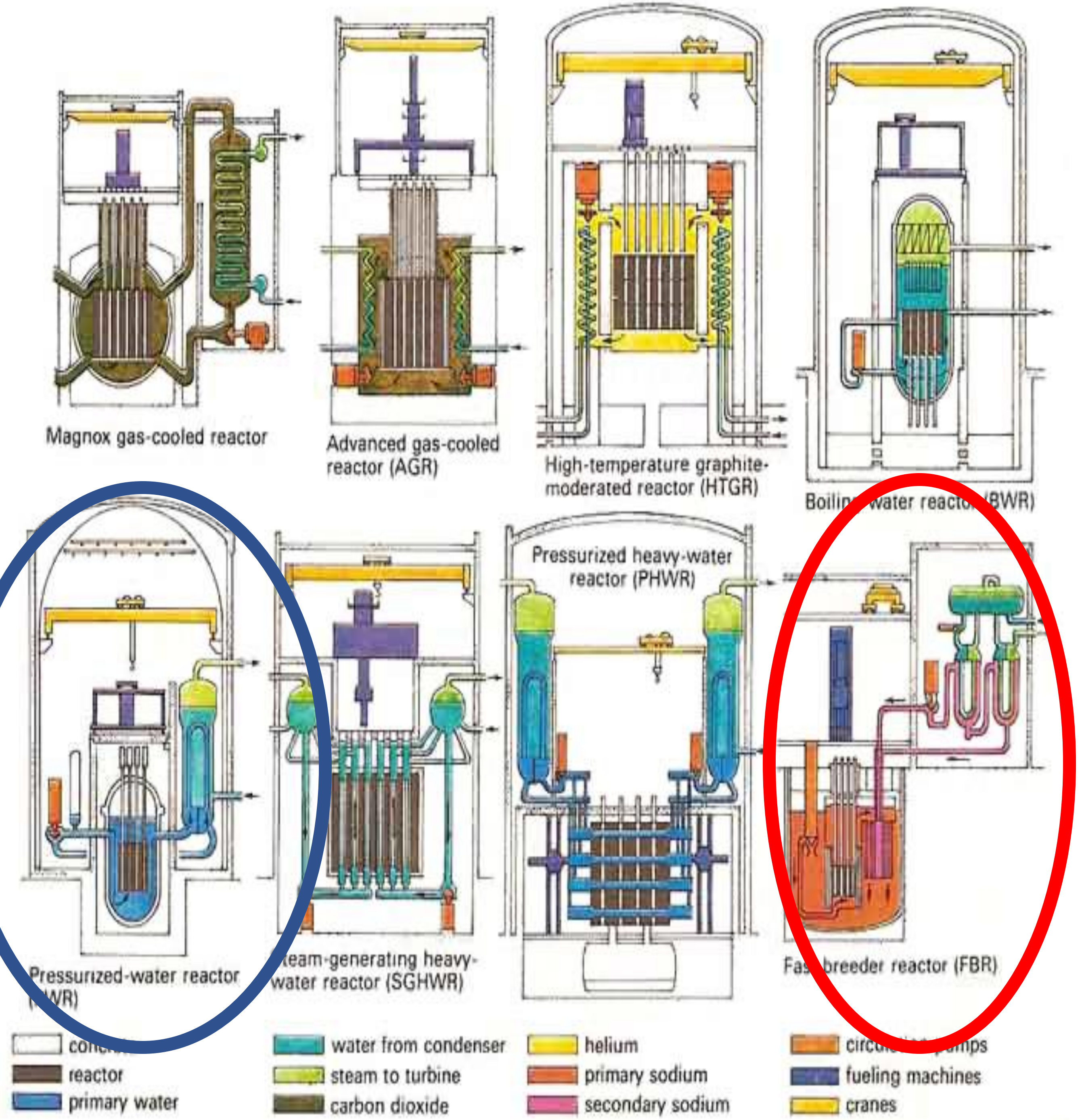


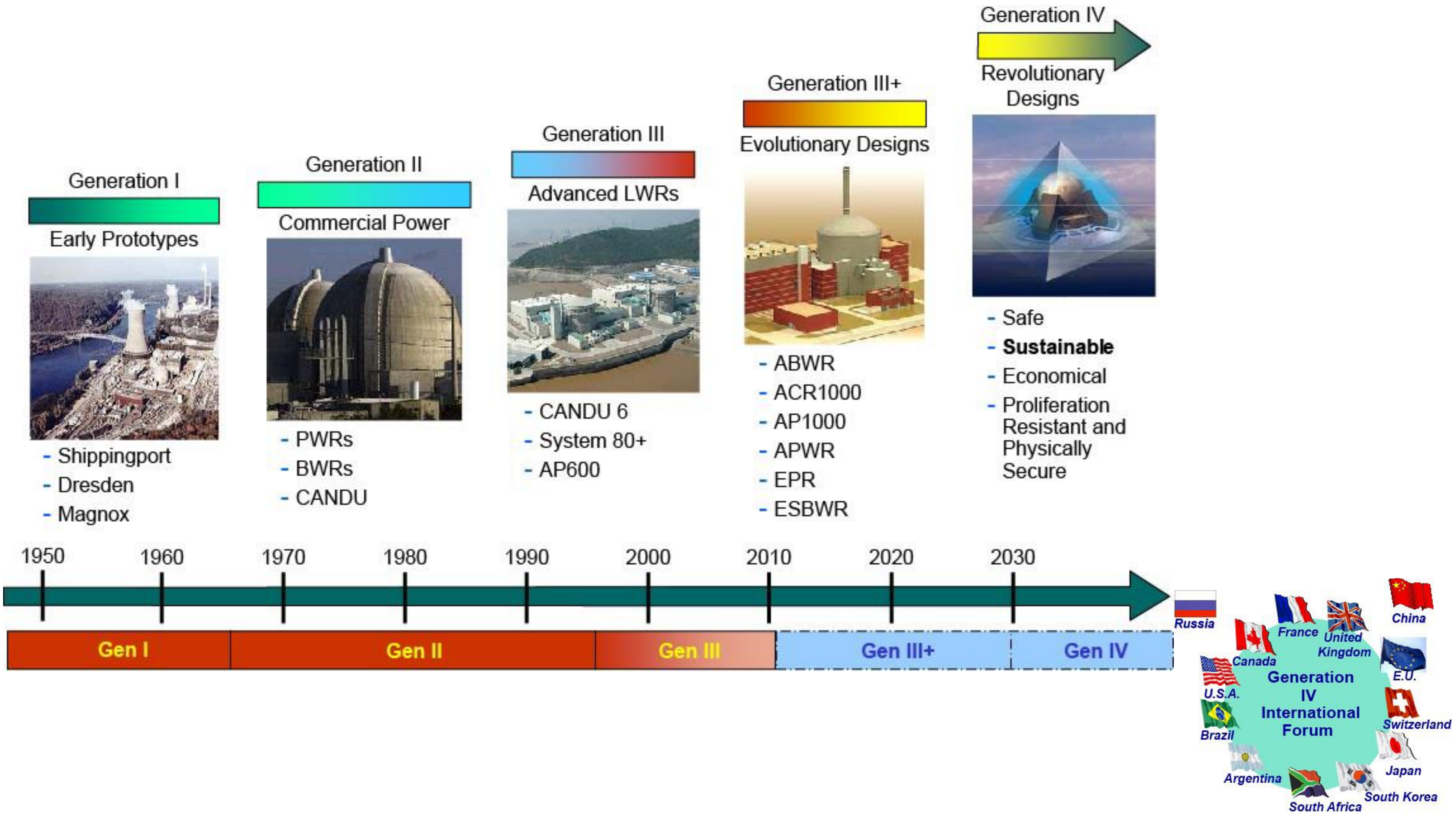
FIG. 2

Theoretical fuel cycle of a fast isogenerator reactor fleet for a production of 400 TWh/year.

Pressurized Water Reactor (PWR)

Réacteur à Eau Pressurisée (REP)





Generation I
Early Prototypes
- Shippingport
- Dresden
- Magnox
Generation II
Commercial Power
- PWRs
- BWRs
- CANDU
Generation III
Advanced LWRs
- CANDU 6
- System 80+
- AP600
Generation III+
Evolutionary Designs
- ABWR
- ACR1000
- AP1000
- APWR
- EPR
- ESBWR
Generation IV
Revolutionary Designs
- Safe
- Sustainable
- Economical
- Proliferation Resistant and Physically Secure
1950
1960
1970
1980
1990
2000
2010
2020
2030
Gen I
Gen II
Gen III
Gen III+
Gen IV
Generation IV International Forum
Russia
France
United Kingdom
China
Canada
E.U.
U.S.A.
Switzerland
Brazil
Japan
Argentina
South Africa
South Korea

Integration of Nuclear energy in a decarbonated economy…

SMR ?

- Small reactors « small is beautiful »…
- Investment more distributed in time
- Useage more suitable for less intensive use
  - Business case : heat generation, island provision, far from networks, dessalination plant
- Easier to develop passive safety concepts
- Easier to build?

- Overall cost majored?
- Fuel production with higher enrichment?
- Proliferation?
- Fuel cycle
- Issue of stable provision of energy for industries not able to stop…

Renewable energy and nuclear energy ?

- **Providing an additional electricity production to match the up and downs of renewables**? « en même temps »…

- **Long period adaptation** (« suivi de charge »)

  => well established but with very strict condition of operation

- **High frequency adaptation** (« modulation »)

  => May trigger alternating thermal stresses and thermal incompatibilities

  => operating difficulties

  => Possible damage induced on the system

NOT A SAFETY ISSUE, BUT A DISPONIBILITY QUESTION… AND COST CONSEQUENCES

CONCLUSIONS…

After decades of intensive diabolisation and shameless desinformation…

- Nuclear energy is a mature technology for centralised and decarbonated electricity
- Using materials and space efficiently
- Safe in its operation and responsible whith its waste

- Able to function efficiently in an extended electricity network
- Can be adapted to other use (heat generation…) provided the business model is serious
- The coexistence with intermittent sources is neither catastrophic , nor innocent, and will mst likely lead to difficulties of operation, and enhanced damaged leading to lower disponibility