DE LA RECHERCHE À L'INDUSTRIE

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URANIUM IN PHOSPHATE ROCKS AND FUTURE NUCLEAR POWER FLEETS

S. GABRIEL, A. BASCHWITZ, G. MATHONNIERE

sophie.gabriel@cea.fr

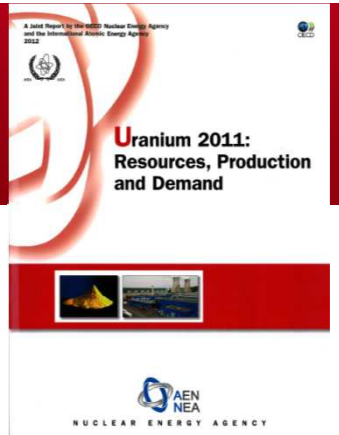
CEA, DEN/DANS/I-tésé

Presented by A. MONNET *CEA, DEN/DANS/I-tésé*

Plan

- Supply of Uranium
  - Sources of information
  - Conventional resources
  - Unconventional resources
    - Seawater
    - Phosphate rocks
- Very long term demand – Energy scenarios
- Supply and Demand adequacy
  - Exclusive deployment of PWR
  - Possible deployment of FR from 2040

Natural Uranium resources – Information



Global information :

- « The Red Book » (OECD/NEA and IAEA publication)
  - **Conventional**: established history of production (primary product, co-product or important by-product)
  - **Unconventional**: very low grade or minor by-product
    - **Seawater**
    - **Phosphate rocks**
  - **Secondary supply**: already extracted
- World Nuclear Association
- Annual report of companies
- Other sources…

Technical publications

Conventional Uranium resources (Red Book 2011)

	Identified		Undiscovered	
Recoverable at costs	Reasonably Assured	Inferred	Pronosticated	Speculative
< 40 $/kg U	0.5	0.2	1.6	
40-80 $/kg U	1.5	0.9		
80-130 $/kg U	1.4	0.8	1.1	
130-260 $/kg U	0.9	0.8	0.1	
Sub total	4.4	2.7	2.8	7.6
Total	7.1 MtU		10.4 MtU	

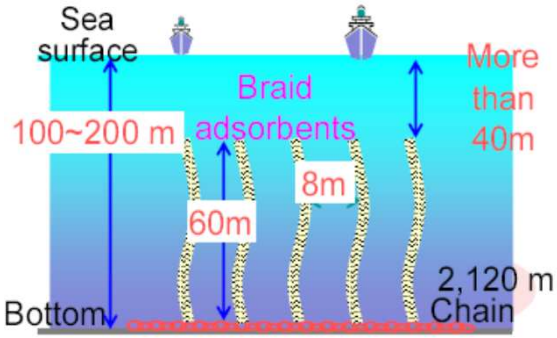
Separate categories reflecting different levels of confidence in the quantities reported

All resource categories are defined in terms of costs of uranium recovered at the ore processing plant.

Unconventional Uranium resources: Seawater

4,000 MtU at very low grade (3,3 µg/l)….

- Process huge volumes (1,200 tU/yr require at least to process 1 km^3/d of water)
  - Active pumping : Energy return <1
  - Strong natural currents
  - Restricted maritime areas



Source JAEA

- Extraction technology has been proven on a laboratory scale, but
  - Cost estimates are very high, lot of uncertainties
  - Energy rate of return ?
  - Environnemental balance?
  - **U as a By-product ?**

…Major technical breakthrough needed

Unconventional Uranium resources: Phosphate rocks (1/2)

Phosphate rocks reserves + U content => U reserves in phosphates rocks :

	Phosphate reserve	**Uranium** reserve
De Voto & Steven (1979)	223 Gt (US) 293 Gt (Free World)	22 MtU 29 MtU
Red Book (2009)	-	7.3-7.6 **22 MtU**
USGS (2011)	65 Gt	

Phosphate reserve
65 Gt

100 ppm U
72% phosphoric acid
83,7% recovery

3.9 Mt U reserve

Unconventional Uranium resources: Phosphate rocks (2/2)

- U from Phosphate : By-product or Primary product ?

Phosphate production
176 Mt
(U by-product)

100 ppm U
72% phosphoric acid
83,7% recovery

10.6 ktU/yr

100-150 $/kgU

Uranium production
(U primary product)

Phosphoric acid cost: **257 $/t**
Specific cost for U recovery: **130 $/kgU**
100 ppm U
72% phosphoric acid
83,7% recovery

« No limit capacity »

≈ 3,000 $/kgU

Limits of available Uranium reserves

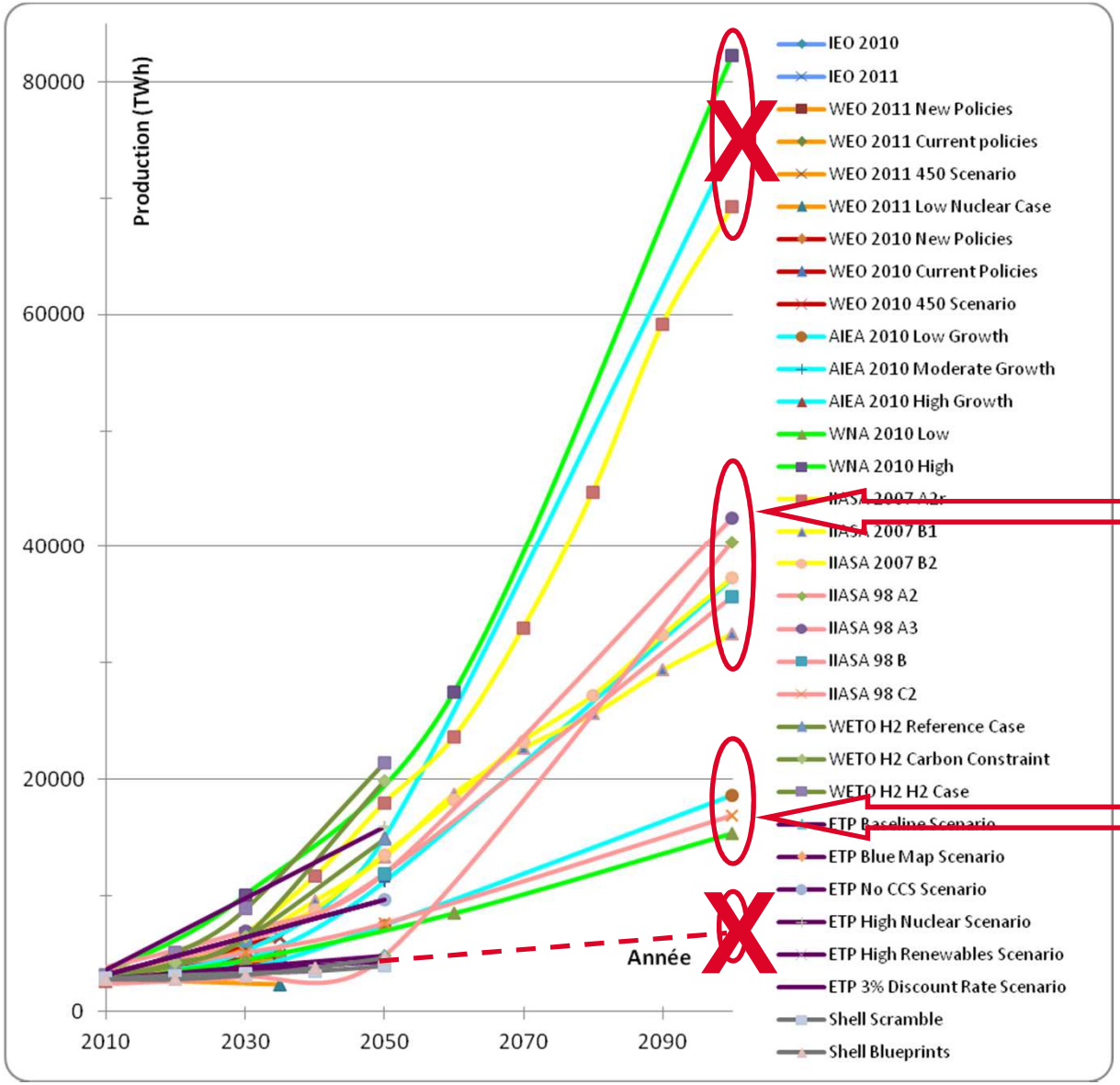
- **7 Mt :** **Identified** conventional uranium resources

- **21 Mt :** **17 Mt** of conventional resources
  (**7 Mt** of **identified + 10 Mt** of **undiscovered**)
  + 4 Mt from phosphate rocks

- **39 Mt :** **17 Mt** of conventional resources
  (**7 Mt** of **identified + 10 Mt** of **undiscovered**)
  + 22 Mt from phosphate rocks (former optimistic estimate)

- **90 Mt :** **very optimistic view** rather than an evaluation
  (takes into account the hope that mining exploration will find substantial new resources, but is not a geologist point of view)

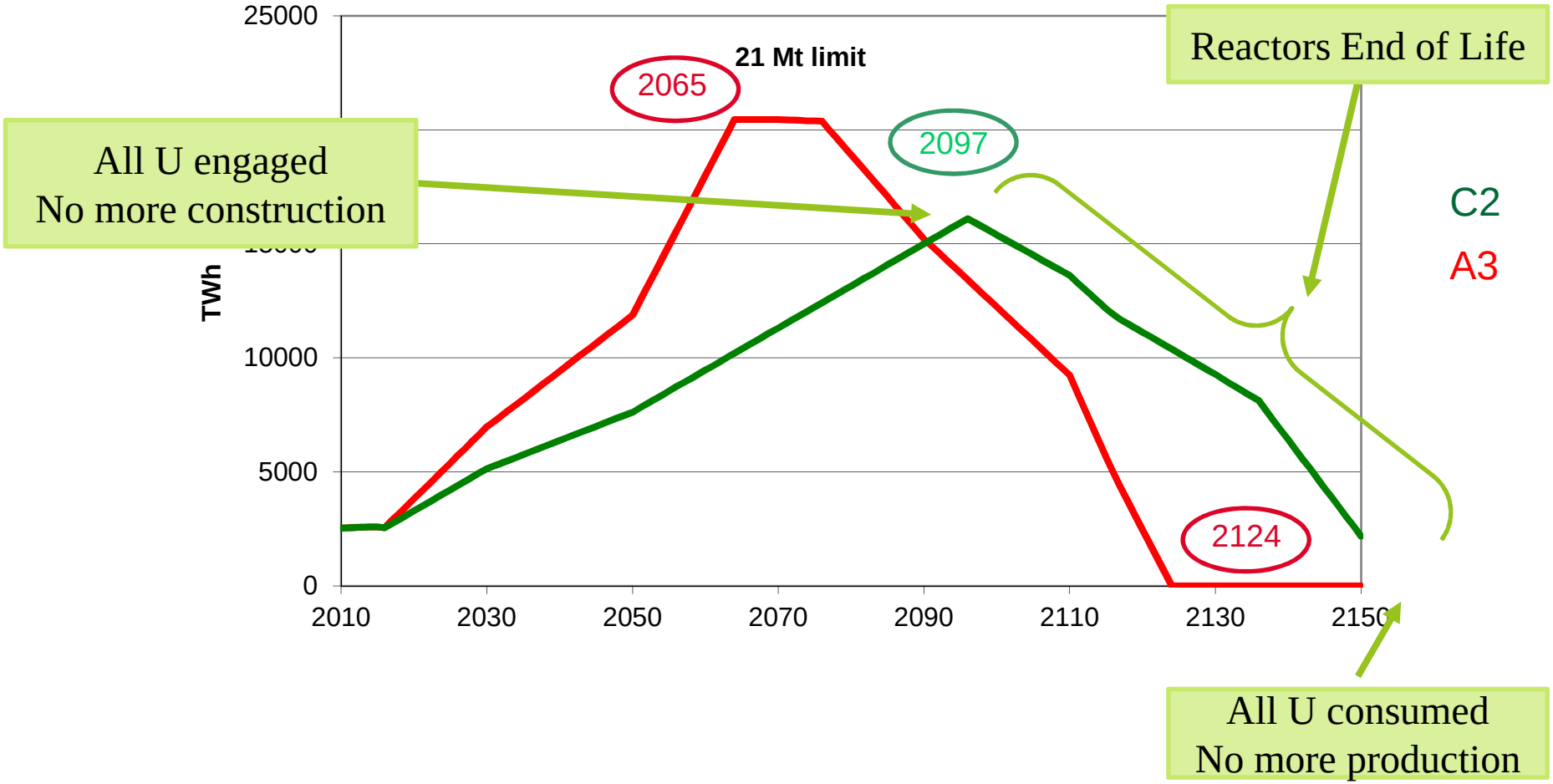
Forecasting studies on the development of nuclear power



Chosen Scénarios IIASA 98

Exclusive deployment of PWRs (1/3)

- Only PWRs can be built.
- When the consumed and engaged U exceed the limit, building a new reactor is impossible.



Exclusive deployment of PWRs (2/3)

7 Mt : Identified conventional uranium resources

21 Mt : 17 Mt of conventional resources (**7 Mt** of **identified + 10 Mt** of **undiscovered**) **+ 4 Mt** from phosphate rocks

39 Mt : 17 Mt of conventional resources (**7 Mt** of **identified + 10 Mt** of **undiscovered**) **+ 22 Mt** from phosphate rocks

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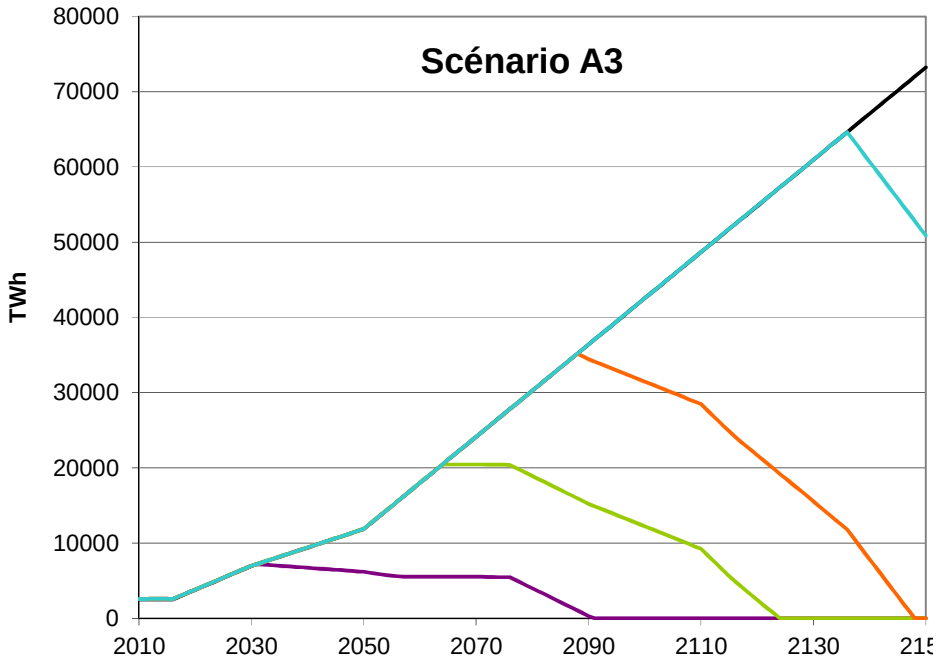
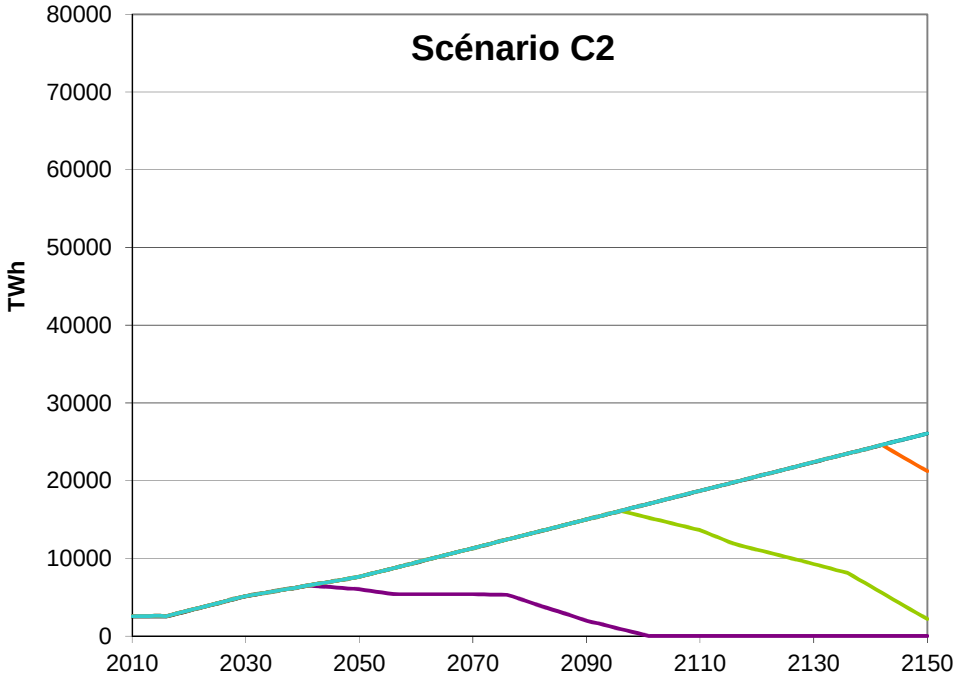




Exclusive deployment of PWRs (3/3)

Scenario	A3	C2
7 Mt limit	2091	2100
21 Mt limit	2124	After 2150
39 Mt limit	2148	After 2150

Expected date of all U consumed

(No more PWR production)

Expected date of all U engaged

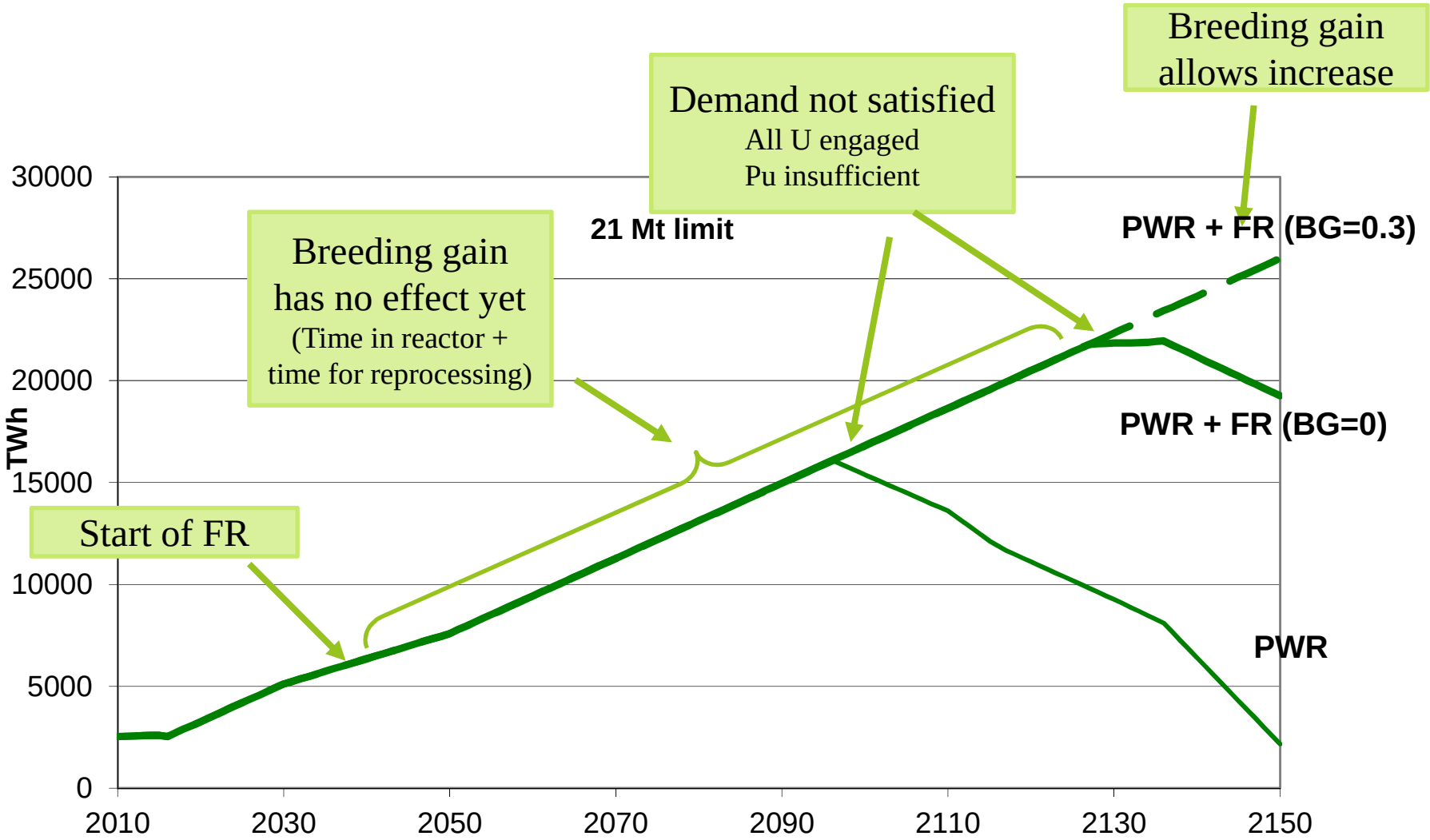
(No more nuclear construction (PWR))

Scenario	A3	C2
7 Mt limit	2032	2042
21 Mt limit	2065	2097
39 Mt limit	2089	2143
When the limit drops from 39 Mt to 21 Mt, the shortage occurs:	25 years earlier	45 years earlier

FR deployment - Assumptions

- From 2040, building Fast Reactors (FR) will be given a top priority.
  - **Self-sufficient** reactors
  - **Breeder** reactors with a Breeding Gain (BG) of 0.3
- All the spent fuel can be reprocessed
- No geopolitical consideration (the World is a whole unit)
- If there is an insufficient stock of available Pu but still a sufficient supply of U, PWRs are built.
- If both U and Pu are lacking, no reactors will be built.

Possible deployment of FR from 2040 (1/3)



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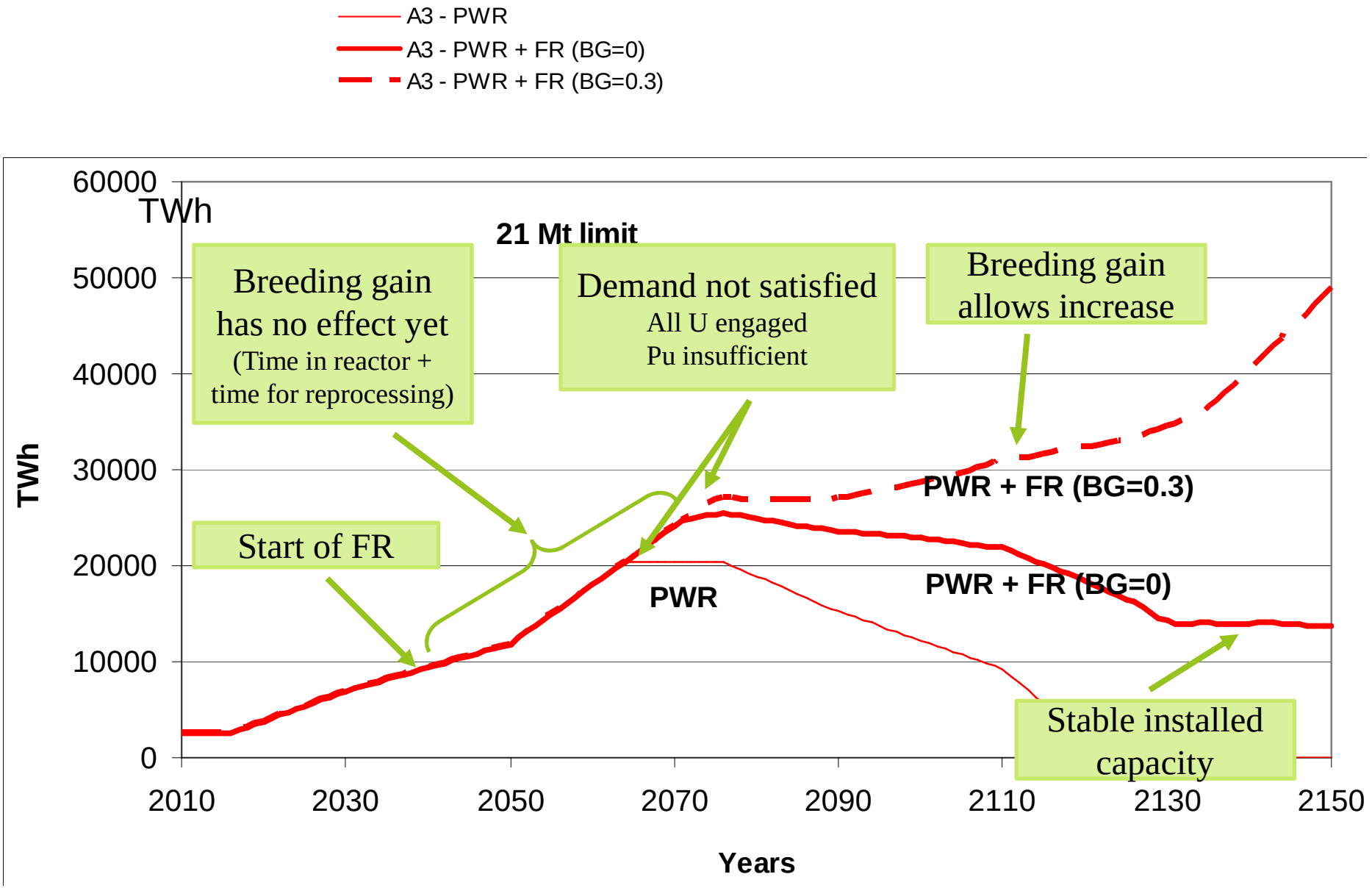


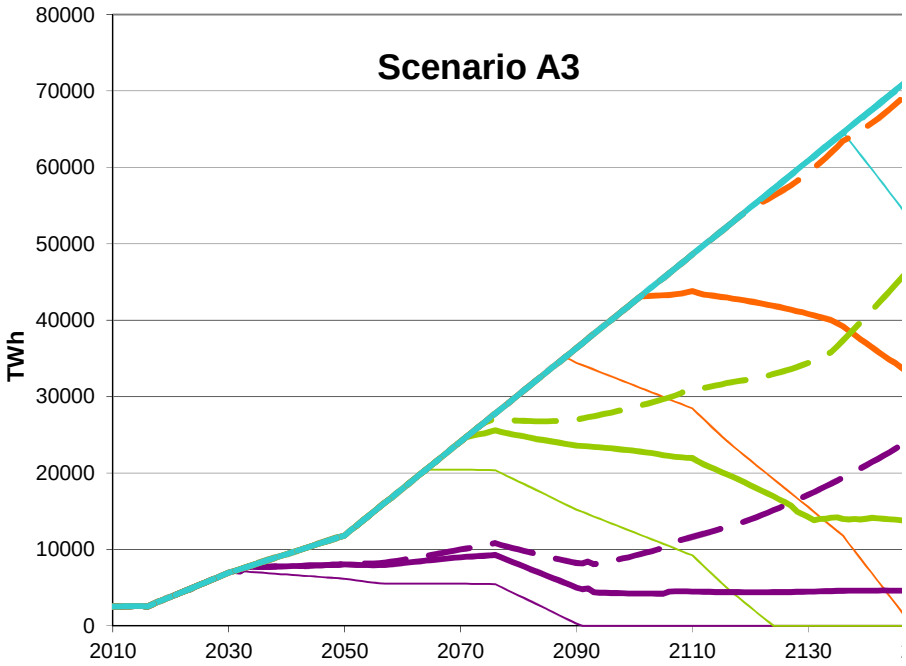
Possible deployment of FR from 2040 (2/3)

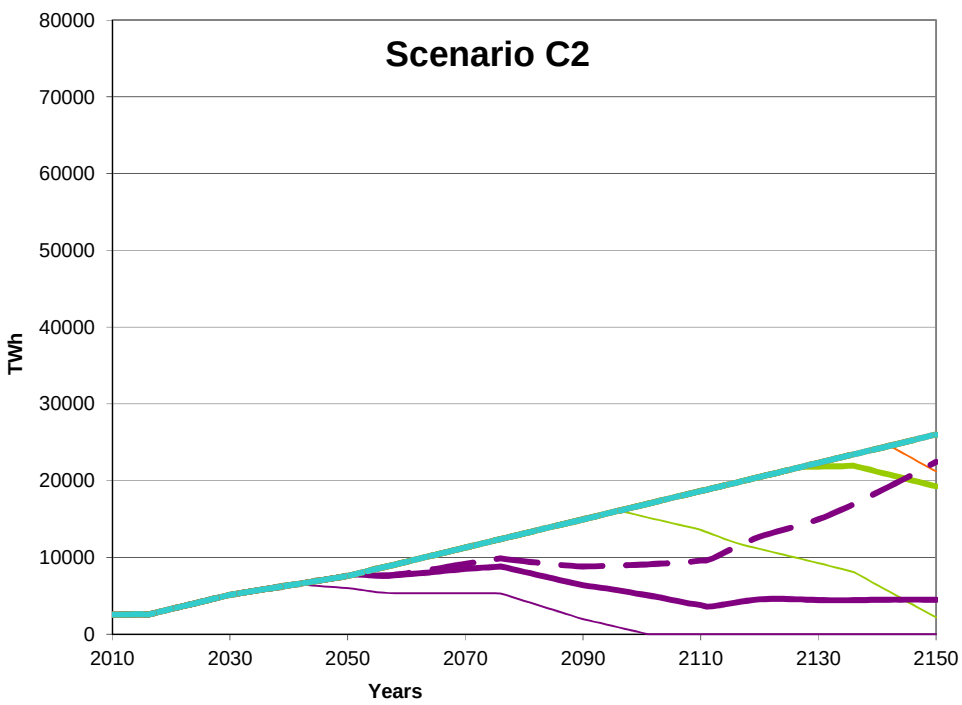
7 Mt : Identified conventional uranium resources

21 Mt : 17 Mt of conventional resources (**7 Mt** of **identified + 10 Mt** of **undiscovered**) **+ 4 Mt** from phosphate rocks

39 Mt : 17 Mt of conventional resources (**7 Mt** of **identified + 10 Mt** of **undiscovered**) **+ 22 Mt** from phosphate rocks

90 Mt : very optimistic view rather than an evaluation





Possible deployment of FR from 2040 (3/3)

Dates when nuclear power requirements are no longer satisfied

U limit	Breeding gain	A3	C2
7 Mt	0	2032	2052
	0.3	2032	2052
21 Mt	0	2072	2128
	0.3	2075	\
39 Mt	0	2102	\
	0.3	2121	\

- Regardless of the level of resources
  - the transition to FRs is necessary
  - the FRs should be breeder

Conclusion

A large-scale deployment of nuclear reactors will require more Uranium

U resources are limited and not well known:

- U from Seawater : Major technical breakthrough needed
- U from phosphate rocks : 4 Mt, an upper bound limit

=> Mining exploration is necessary
=> What about the annual production capacity?

If only PWRs are deployed in this century:

- All the U identified resources are engaged before 2050 and consumed before the end of the century

=> The deployment of PWR only is not sustainable in the long term
=> The FR deployment is inescapable for a long term development of nuclear power

But the installation rate of the FR fleet is limited by the Pu availability…