ASPO 2007

NUCLEAR AND OIL :

Towards a long term symbiosis ?

Pierre-René Bauquis

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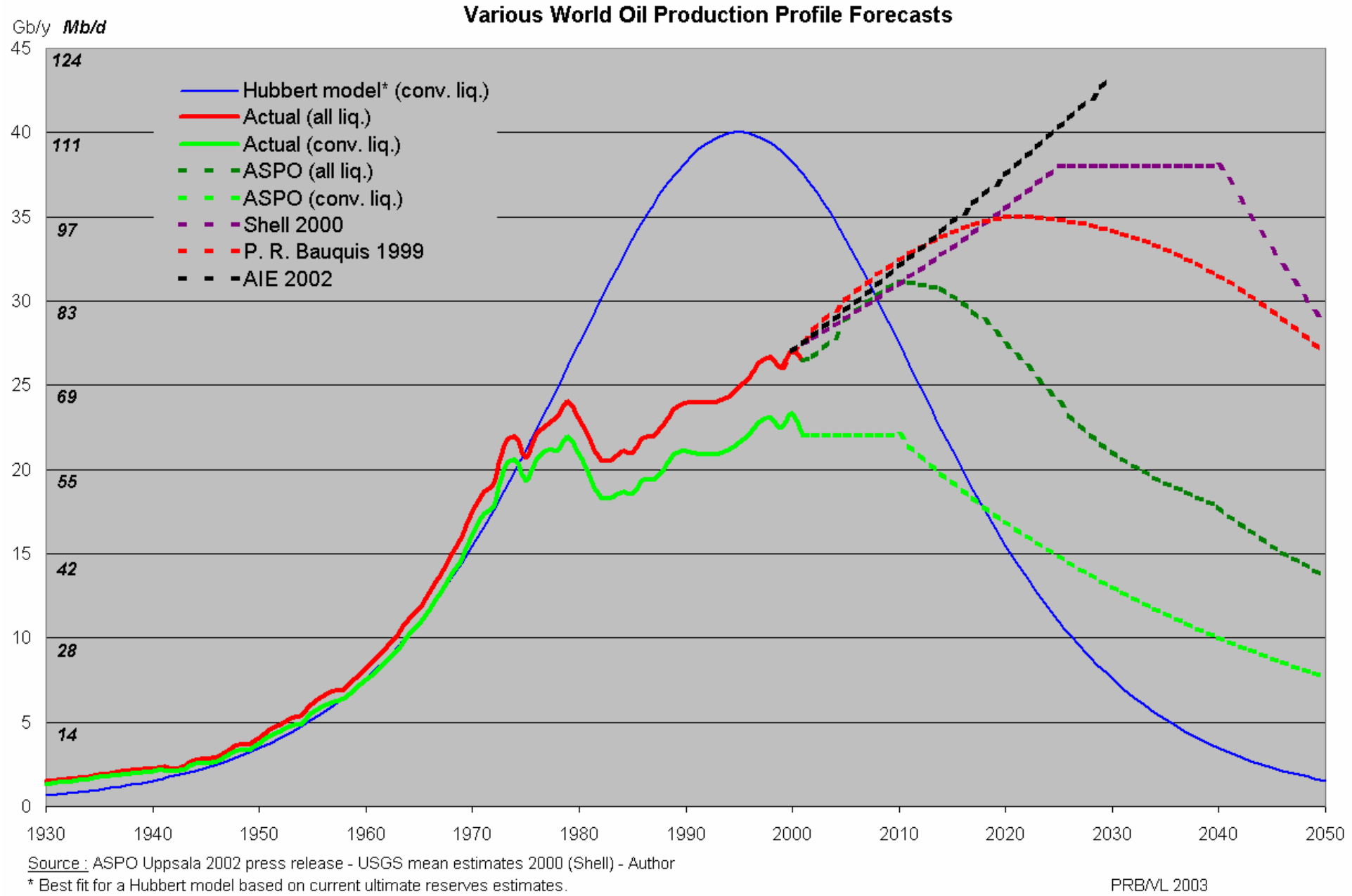
Major constraints facing oil and gas

- Production peaks
- Climate change

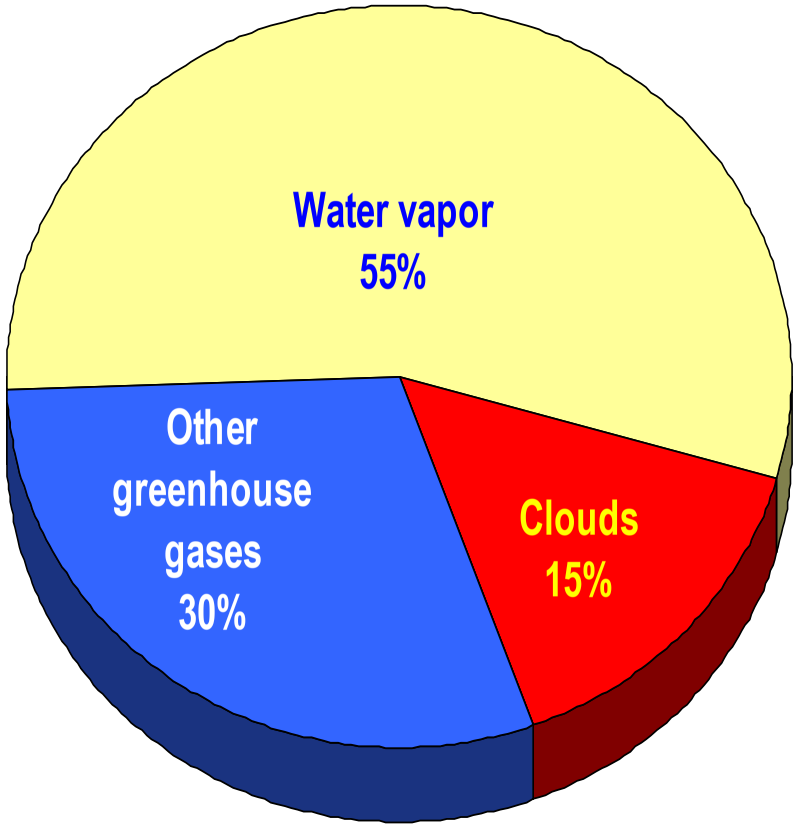

Various World Oil Production Profile Forecasts
Gb/y
Mb/d
45
124
40
111
35
97
30
83
25
69
20
55
15
42
10
28
5
14
0
Hubbert model* (conv. liq.)
Actual (all liq.)
Actual (conv. liq.)
ASPO (all liq.)
ASPO (conv. liq.)
Shell 2000
P. R. Bauquis 1999
AIE 2002
1930
1940
1950
1960
1970
1980
1990
2000
2010
2020
2030
2040
2050
Source : ASPO Uppsala 2002 press release - USGS mean estimates 2000 (Shell) - Author
* Best fit for a Hubbert model based on current ultimate reserves estimates.
PRB/VL 2003

Conclusions about "peak oil"

- **Since June 2006 it can be considered that views about Peak Oil in France have become reasonably similar :**
  - TOTAL : Thierry Desmarest – around 2020 / around 100 Mb/d
  - ASPO France : J. Laherrère – around 2015 / less than 100 Mb/d
    P.R. Bauquis – around 2020 / around 100 Mb/d
  - IFP : Y. Mathieu –undulated plateau 2015/2030 – less than 100 Mb/d

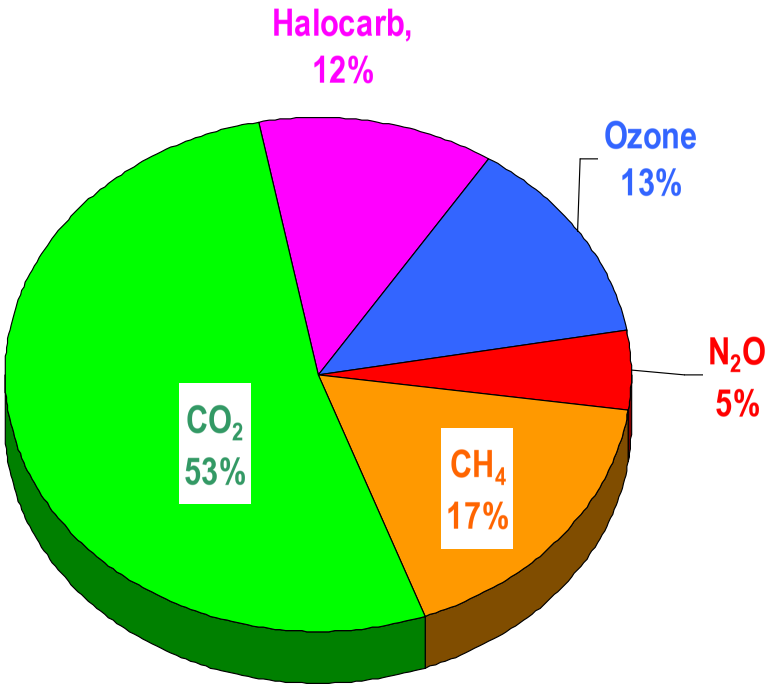
- **This point of view differs markedly from those among the "optimists" who believe that Peak Oil is not "reserves related" but a political problem : insufficient investment and restrictive policies about investment by OPEC countries, Russia and Mexico :**
  - Exxon Mobil – June 2006 – "no sign of peak oil"
  - Aramco – June 2006 -"no reserve problem"
  - ENI (Maugeri – Early 2006 - "no foreseeable oil peak"
  - BP : John Browne – May 2006 - "There is no reserves problem"
  - Mike Lynch (ex MIT) – "similar and above 120 Mb/d
  - USGS, DOE, EIA
  - IEA up to end 2006; but in June 2007 IEA position became far more pessimistic

Natural and anthropic contributions to greenhouse effect



Natural

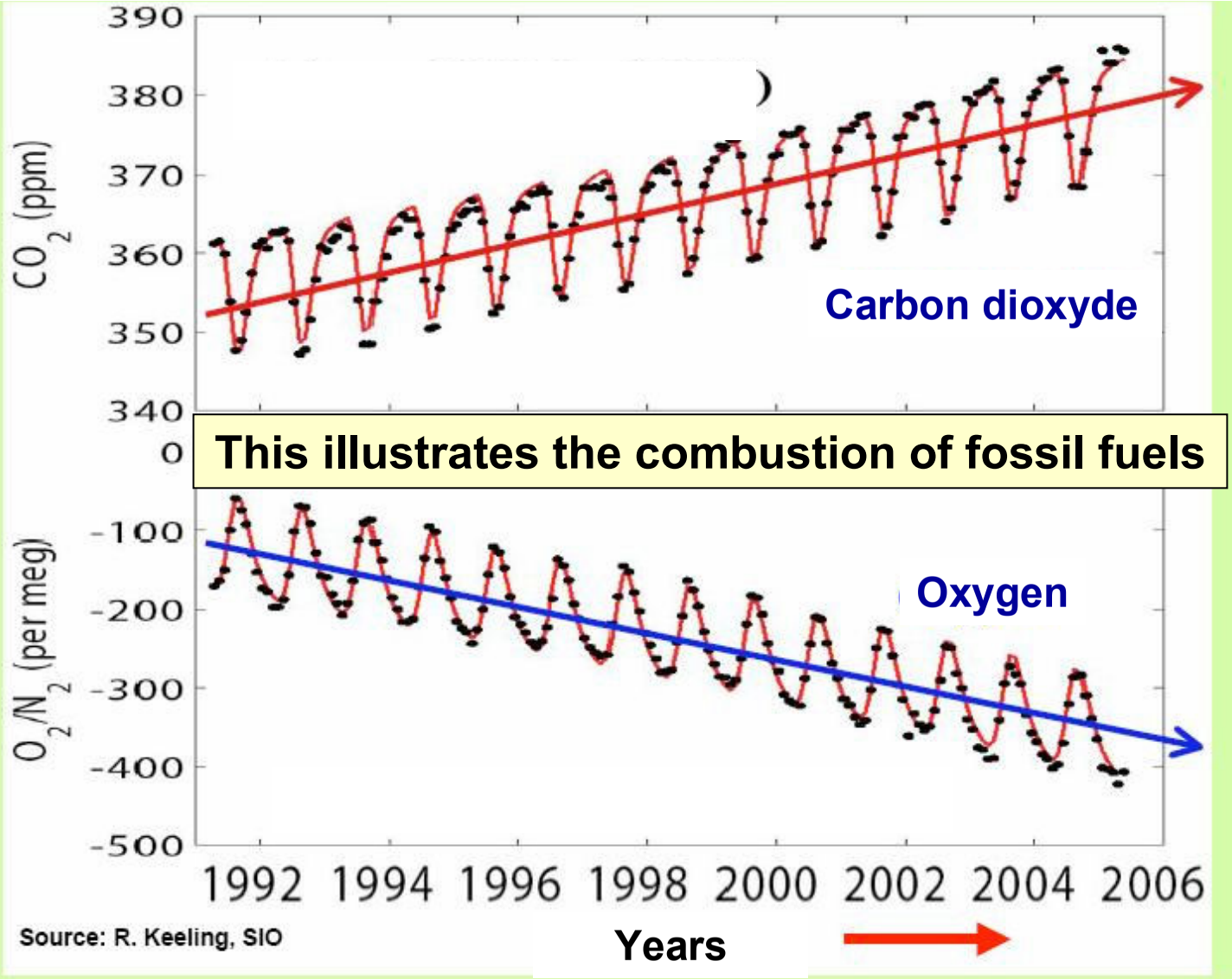
(155 W/m²)



Anthropic

(2.8 W/m²)

Human activities modify greenhouse effect



This illustrates the combustion of fossil fuels

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Oil, gas and nuclear : a historical view

- International oil companies and nuclear
- Oil producing countries and nuclear

International oil companies and nuclear in the past

IN THE 50's AND 60's

- Strong involvement of the oil industry in nuclear :
  - EXXON ➔ invested in the full cycle
    - *Mining*
    - *Fuel Fabrication*
    - *Enrichment*
    - *Reprocessing*
  - SHELL ➔ invested also in the cycle (at a lower level)
  - AGIP ➔ built the first nuclear plant in Italy

IN THE 70's AND 80's

- After the 1973 and 1979 oil shocks some 20 oil companies invested in nuclear :
- SHELL ➔ HTGR reactor with GULF General Atomic (8 letters of intent + 10 letters of interest)
- EXXON, OCCIDENTAL, ELF, TOTAL, etc ➔ in uranium exploration and mining

TODAY : 2005-2007

- Only TOTAL has kept a (small) interest and announced in 2006 and 2007 their intention to "look at nuclear"
- Other IOC's keep silent up to now (but must be "thinking").

Oil producing countries and nuclear

- Up to recently most oil producing countries looked at nuclear energy as a competitor or a threat (multiple declarations)

- One exception : IRAN
  - Under the Shah regime launched a comprehensive nuclear programme from uranium exploration, to enrichment (via Eurodif), and electricity generation (2 major plants decided, including Busheer).

  - These plans were officially "revived" recently, but in the worst possible conditions vis a vis the international community (undeclared programmes, international threats).

- Recently a number of oil producing countries have expressed interest in "looking" at nuclear : Algeria, Arabic peninsula States, Libya, Indonesia…

- This recent interest is focused on two objectives : electricity generation and sea water desalination (Libya, Emirates).

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Oil, gas and nuclear relationship in the future

- Upstream
- Downstream
- Transportation

Oil, gas and nuclear potential relationship in the future
1 - Upstream

- **Supply of :**
  - Electricity
  - Heat (steam)
  - Hydrogen

  by nuclear reactors to upstream oil and gas operations

- **Examples :**
  - Conventional heavy oil production (steam injection)
  - Ultra heavy oils and tar sands (SAGD, upgrading)
  - Shale oil production (electrical process : Shell) (classical processes : High t° heat)

- **Already some public announcements :**
  - Total 2005 : “usefulness of nuclear for Canadian oil Sands"
  - Canadian authorities "Two CANDU reactors needed for 2016-2017" for Canadian Oil Sands exploitation

- **Nuclear steam, electricity and hydrogen should make it possible to extend oil reserves and their production profiles.**

Oil, gas and nuclear potential relationship in the future 2 - Downstream

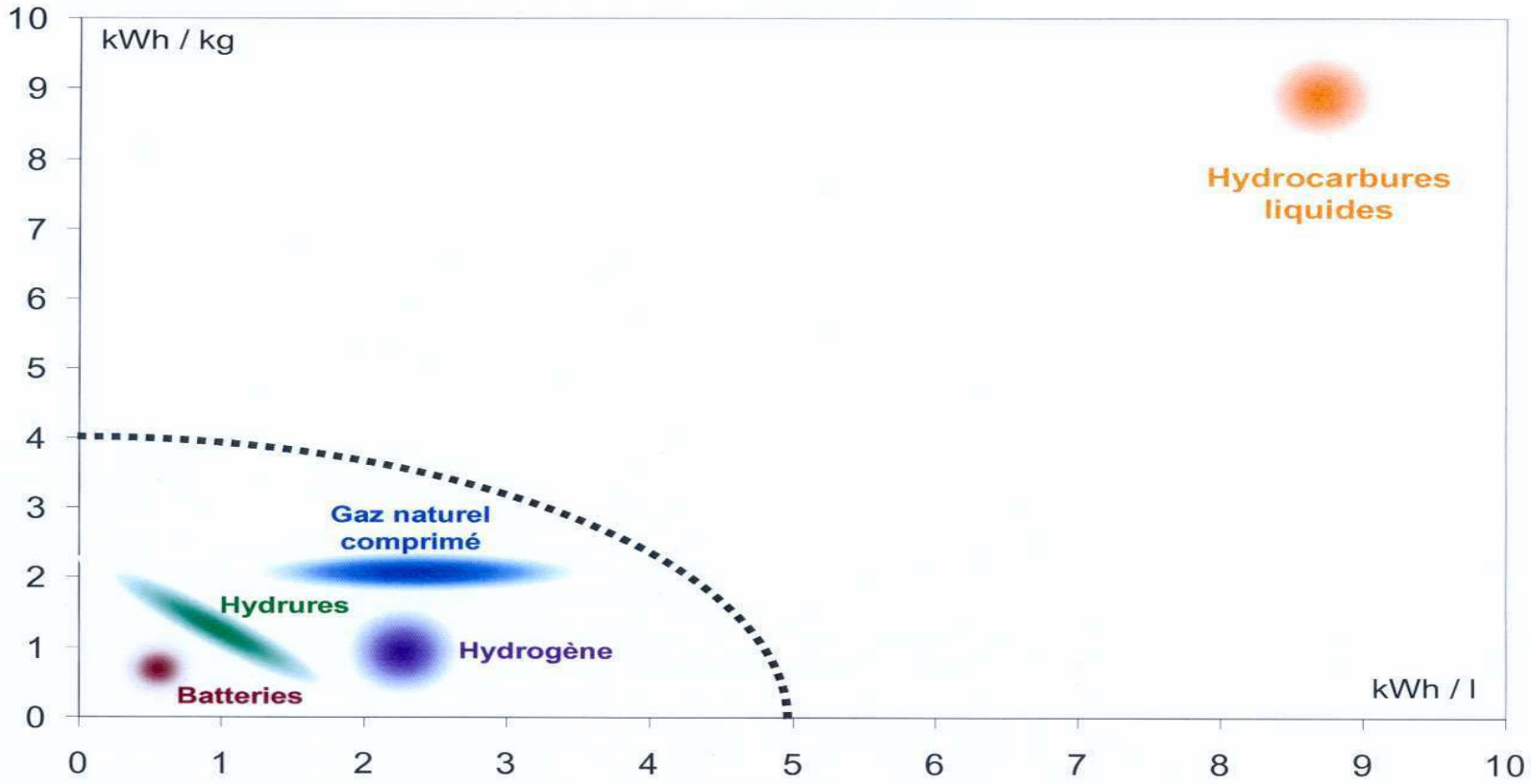
- Regional dedicated nuclear plants providing to large refining zones or petrochemical platforms :
  - Electricity
  - Steam
  - Hydrogen
- Example of potential applications : upgrading units, hydrotreatments :
  - In consuming countries : Gulf of Mexico, Normandy, Rotterdam
  - In producing countries : Middle East, Venezuela, North Africa
- Combined nuclear/gas urban heating systems.
- Nuclear electricity, steam and hydrogen should make it possible to strongly decrease CO_2 emissions from oil and gas downstream operations.

Oil, gas and nuclear potential relationship in the future
3 – Transportation (*)

- The wonderful energy compactness of liquid hydrocarbons
- Which energy sources will power transportation ?
- Hydrogen : a potential challenger for aviation ?

(*) Summary of ASPO 6 (Pisa) presentation by P.R. Bauquis

LIQUID HYDROCARBONS: UNMATCHED ENERGY COMPACTNESS



Fundamentals of nuclear hydrogen - 1

1. In nature two major sources of hydrogen exist : hydrocarbons and water.

2. Nuclear power or renewable energies are the only potential massive sources of hydrogen for the long term. Other solutions are "Shadok solutions"….

3. Hydrogen is a poor energy vector : its transportation costs are ten times those of liquid hydrocarbons, per unit of energy (only exception : injection of hydrogen in existing gas pipeline systems).

4. Hydrogen is a very poor medium for storage in mobile systems, whatever technology is used (5% H_2 mass versus 95% for the containment system in the case of ground transportation).

Fundamentals of nuclear hydrogen - 2

1. If one produces hydrogen as an energy vector, the logic is to attach carbon atoms to create hydrocarbon molecules : those molecules are efficient energy vectors and have excellent storage properties for mobile applications.

2. The future of hydrogen is therefore the production of synthetic hydrocarbons (totally or partially synthetics).

3. The fact of producing such hydrogen through electrolysis or from thermochemical processes is a secondary issue. Terms of comparison between both possibilities will evolve with time.

4. In a first phase, electrolytic processes will make it possible to start the nuclear hydrogen industry as soon as it becomes economically competitive (around 2015/2020?).

What markets for nuclear hydrogen ?

1. Hydrogen has a much higher economic value in its chemical utilizations (refining, petrochemicals, chemicals) than as an energy carrier (the ratio of values vary from one to two up to one to ten times).

2. Therefore, the first markets which will use nuclear hydrogen are the same markets as those utilizing hydrogen today : upgrading units in refineries (conversion of heavy fractions in lighter one or upgrading of ultra-heavy crude oil such as Athabasca or Orinoco), desulfurization, hydrotreating, etc…

3. Transportation utilization of hydrogen, whether gaseous or in a liquid form, should remain "marginal" –at least for ground transport. It is basically an illogical proposition for automobiles.

4. The aviation market could develop after 2050 : liquid (cryo) hydrogen could become the future "Jet Fuel" … even if synthetic Kerosene appears today as a more likely solution for the second half of the 21st century.

Hydrogen and nuclear heat for production of synthetic transportation fuels (XTL)

BIOFUELS (BTL)

H_2 and nuclear heat should make it possible to double or triple the net outputs per hectare (increase from an average in Europe or USA of 1 T net/ha to 2 or 3 T net/ha).

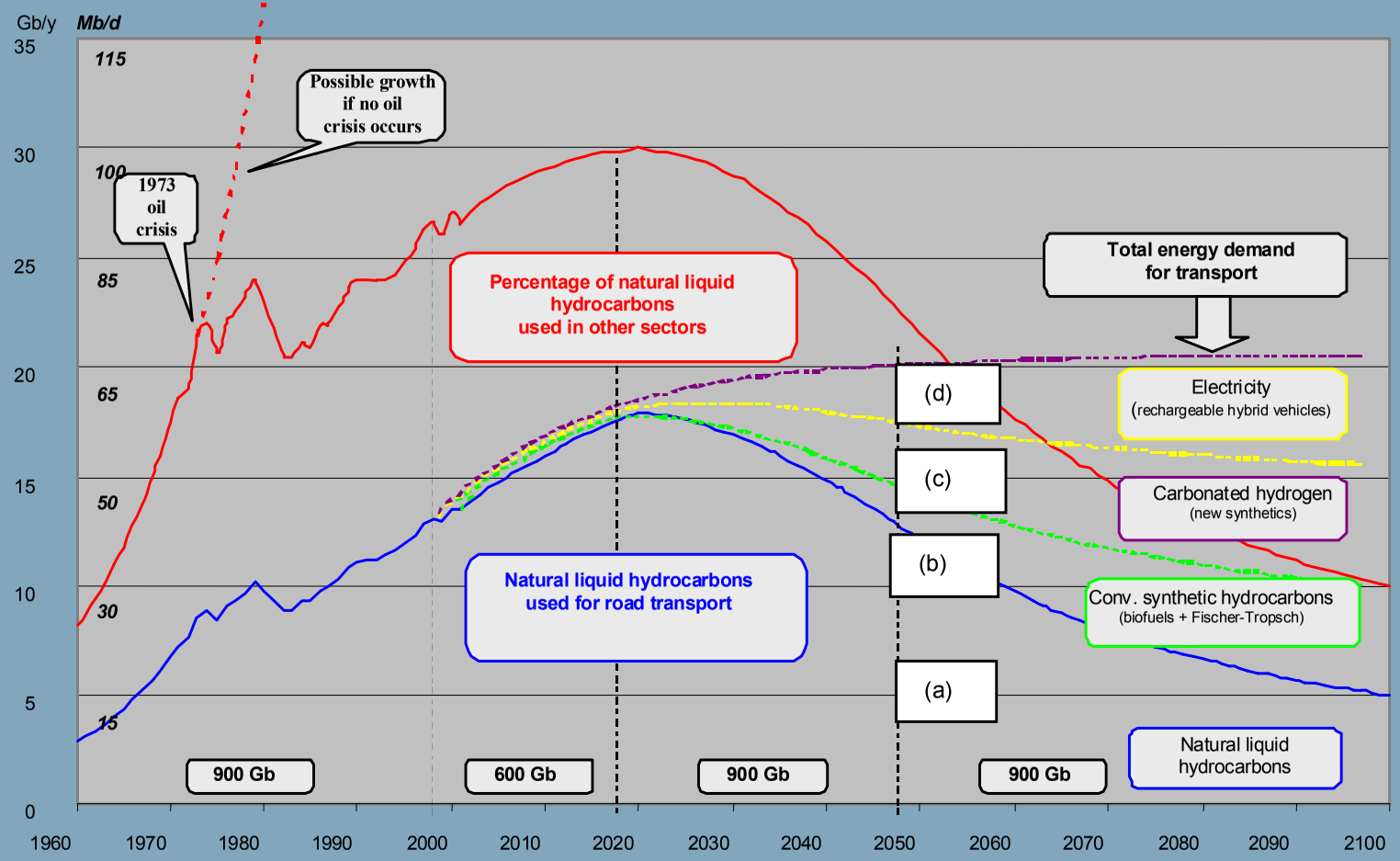
FT SYNFUELS (GTL ou CTL)

H_2 and nuclear heat should make it possible to drastically reduce CO_2 emissions of those processes.

NEW SYNTHETICS (HTL)

the "Hydrogen Carbonation" concept, direct or indirect, was introduced in a publication by P.R. Bauquis in Revue de l'Energie.

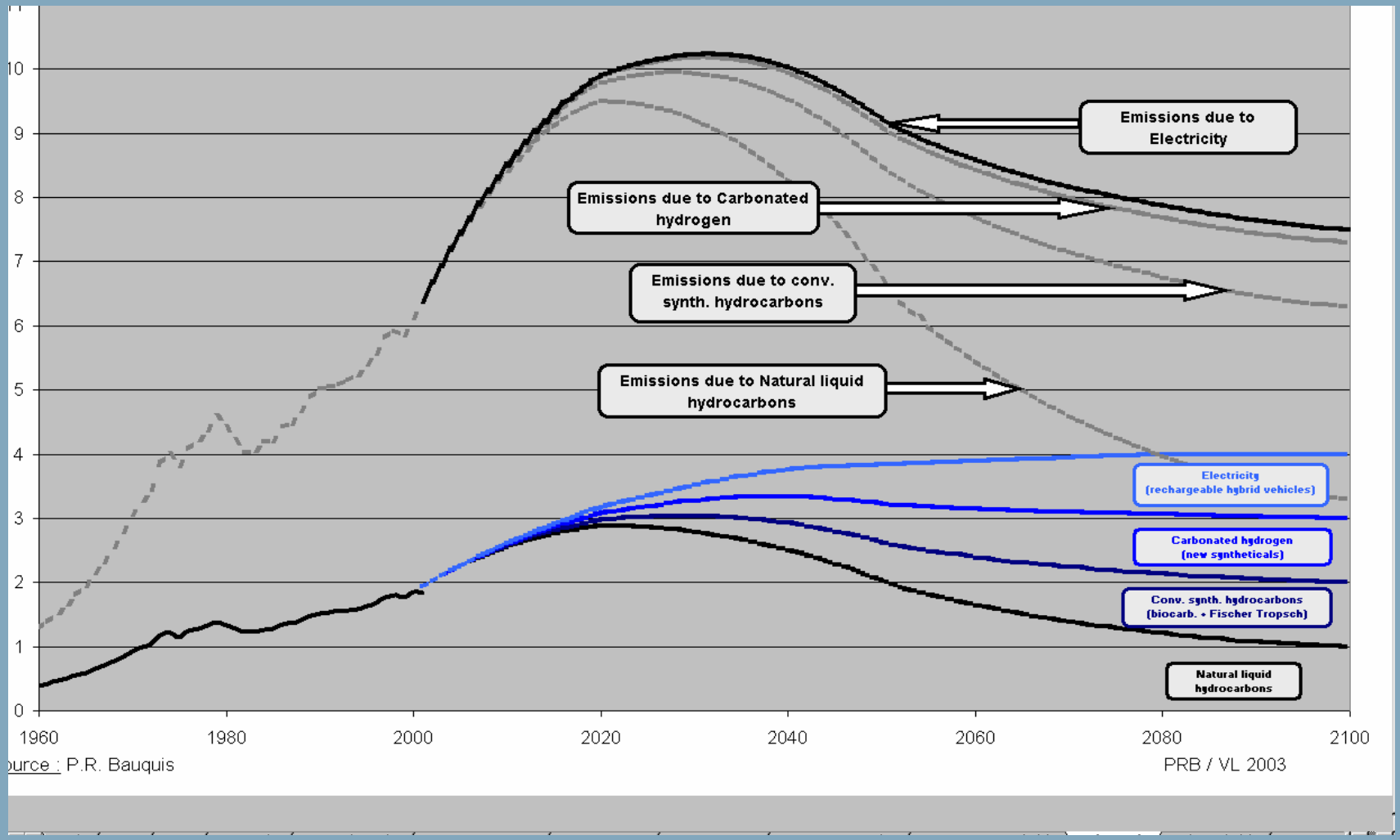
Which energy sources will power transport?
1960 - 2000 - 2100



Source: ASPO data, P.R. Bauquis, October 2002

Energies for Road transports and Carbon Emissions

1960 – 2000 - 2100

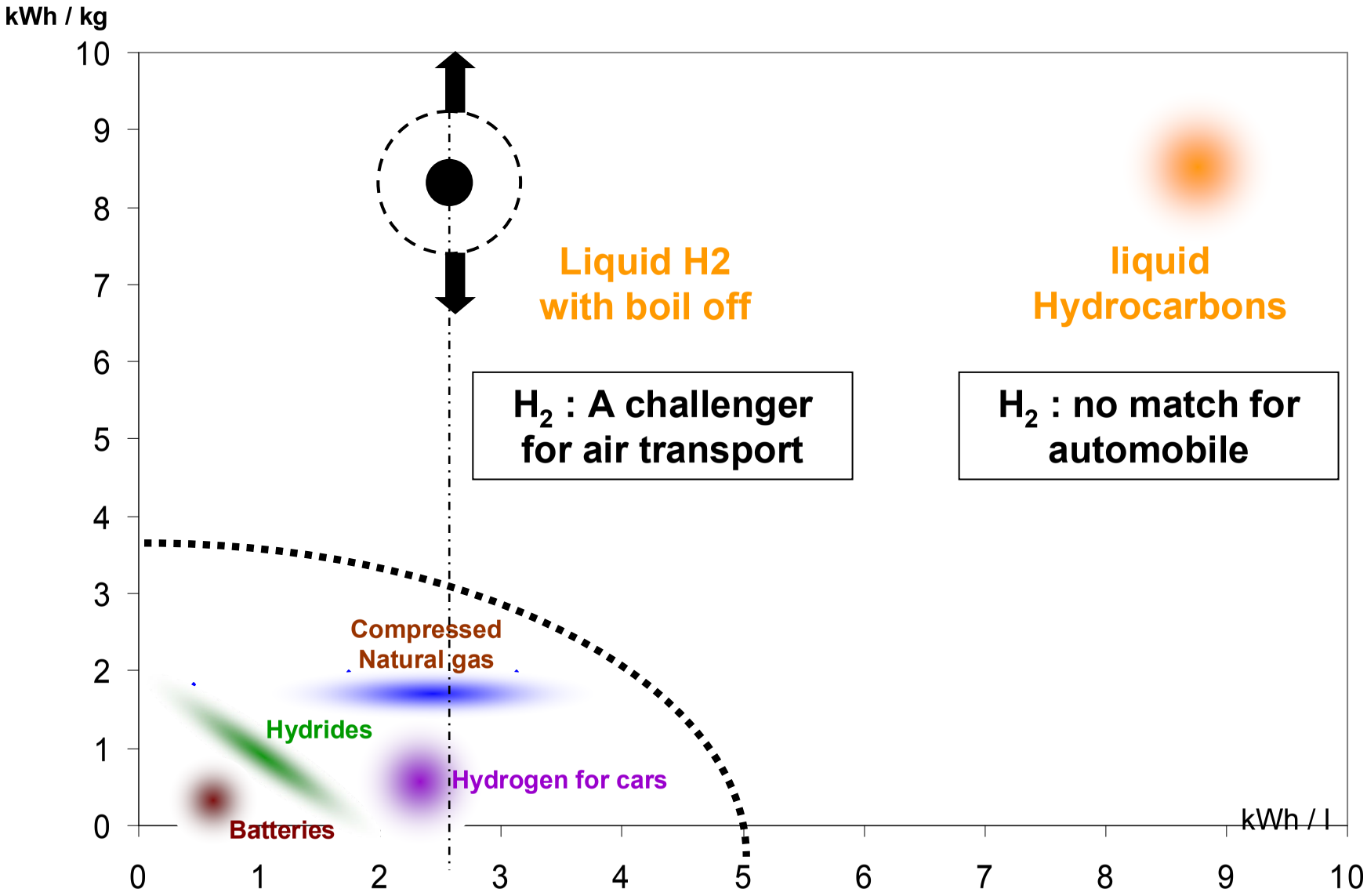


Summary conclusions :

The future marriage of oil products and nuclear electricity should solve long term transportation problems.

2000 : Energy for Ground Transportation	98% oil and gas 1% nuclear 1% others
2100 : Energy for Ground Transportation	30% oil and gas 60% nuclear 10% others

Hydrogen : a potential challenger for aviation ?

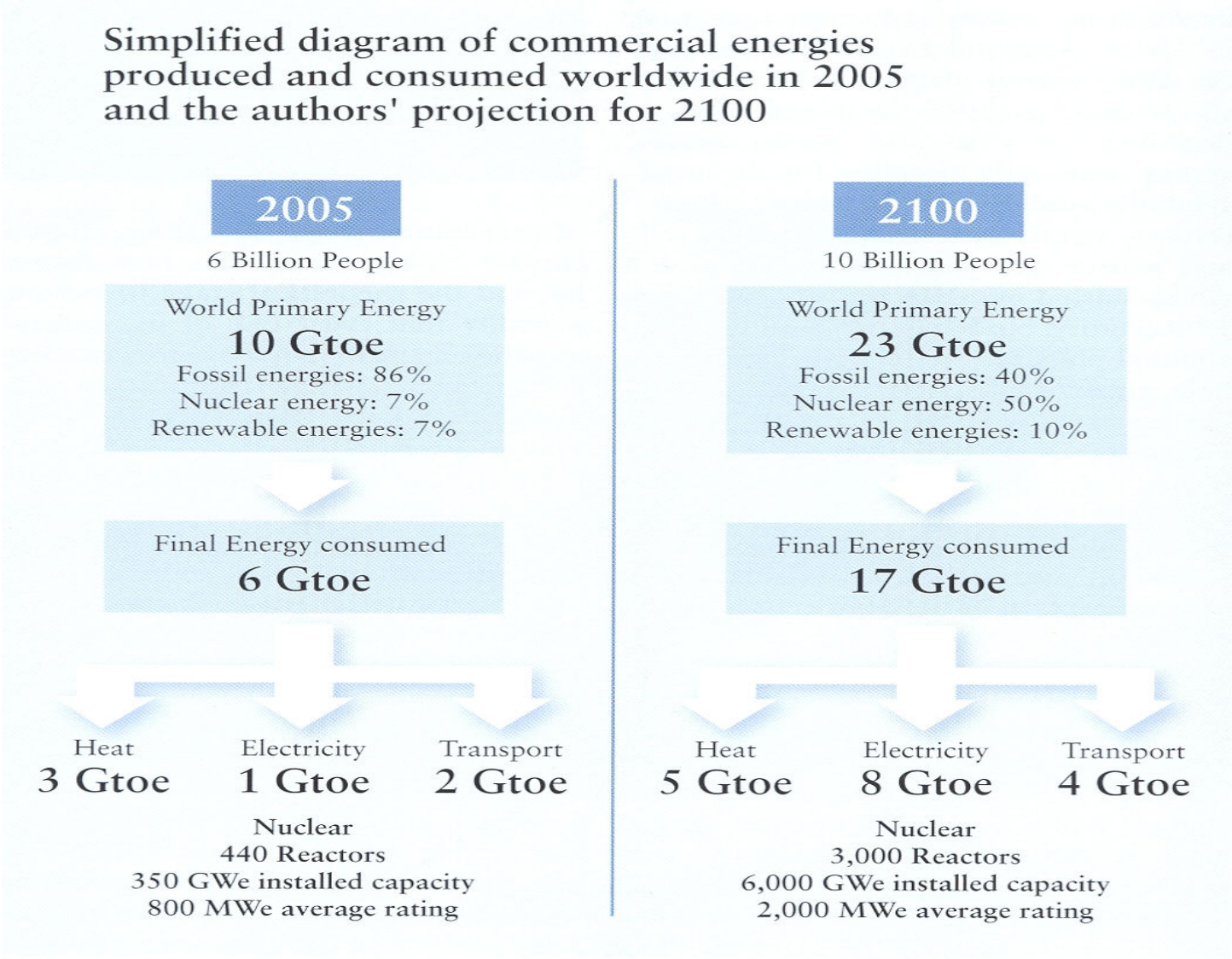


Gaz naturel comprimé : réservoir acier ou composite

④

Resultant long term changes in world energy mix

- Necessary electrification of world energy mix
- Long term utilizations of nuclear



Source : "Nuclear Power. Understanding the future"
Hirlé publications 2nd Q. 2007 by B. Barré and P.R. Bauquis

Cost Price of Electricity produced by the various Types of Power Plant (2005 Conditions)

** In Euros per MWh*

Barrel	Nuclear	Gas	Heavy fuel	Coal	Wind Farm
Capital Costs	20	10	15	15	50
Fuel Costs	10	50	75	25	0
Operating Costs	8	5	6	8	12
TOTAL	38	65	96	48	62
C02 Costs at $20/t	0	7	10	15	0
TOTAL COST WITH CO2	38	72	106	63	62

Cost Price* of Electricity produced by the Various Types of Power Plant (2020 Conditions)

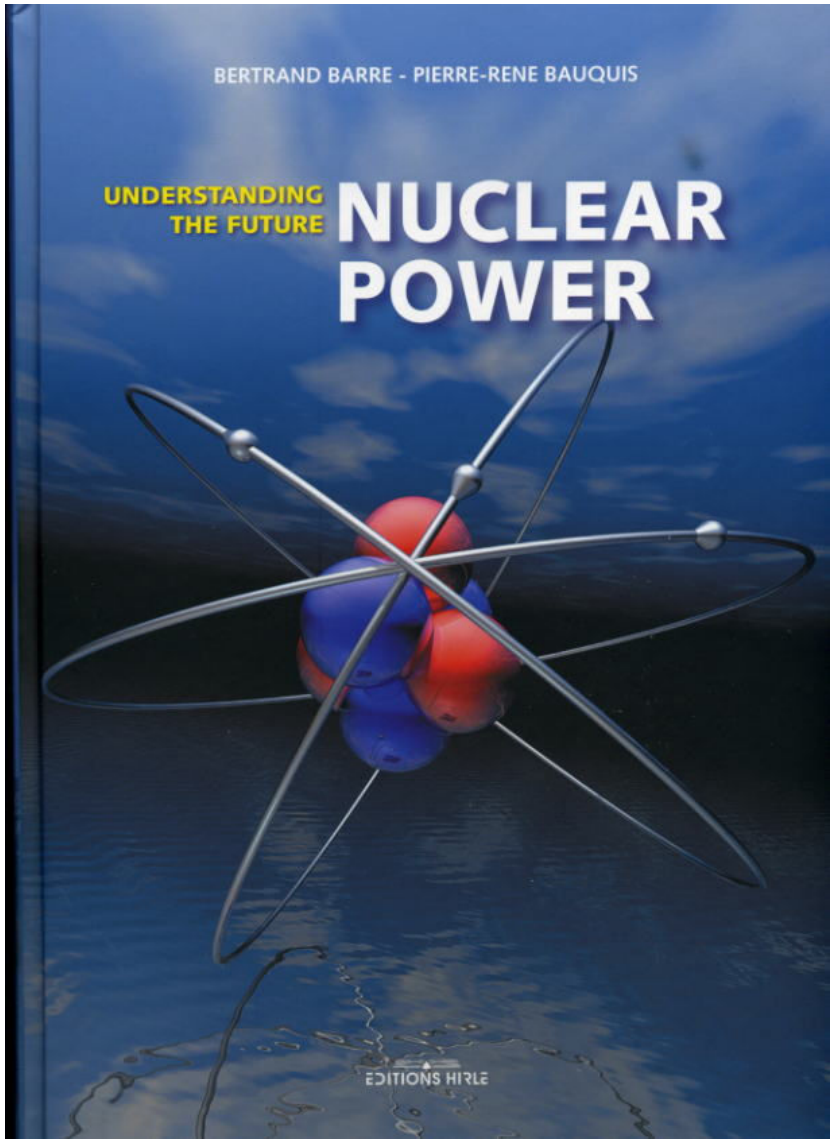
** In Euros per MWh*

	Nuclear	Gas	Heavy fuel	Coal	Wind Farm
Price of Oil $100 /Barrel					
Capital Costs	20	10	15	15	40
Fuel Costs	15	100	150	50	0
Operating Costs	8	5	5	10	10
TOTAL	43	115	170	75	5
C02 Costs at $100/t	0	35	50	75	0
	43	150	220	150	50

Conclusions

- Oil and gas will still be produced beyond the end of the 21st century: paradoxically, it will be the oil and gas industries golden age (high prices, little political interference in those prices).
- Nuclear Golden Age will also prevail all along the 21st century.
- A technical and economic "marriage" between the oil industry and the nuclear industry will develop all along the 21st century as these industries become more and more complementary.
- This marriage will deeply modify world liquid hydrocarbon production profile after peak-oil has occurred. ASPO could contribute to study these new perspectives.

For Further Information…



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