

# World Nuclear Fuel Market

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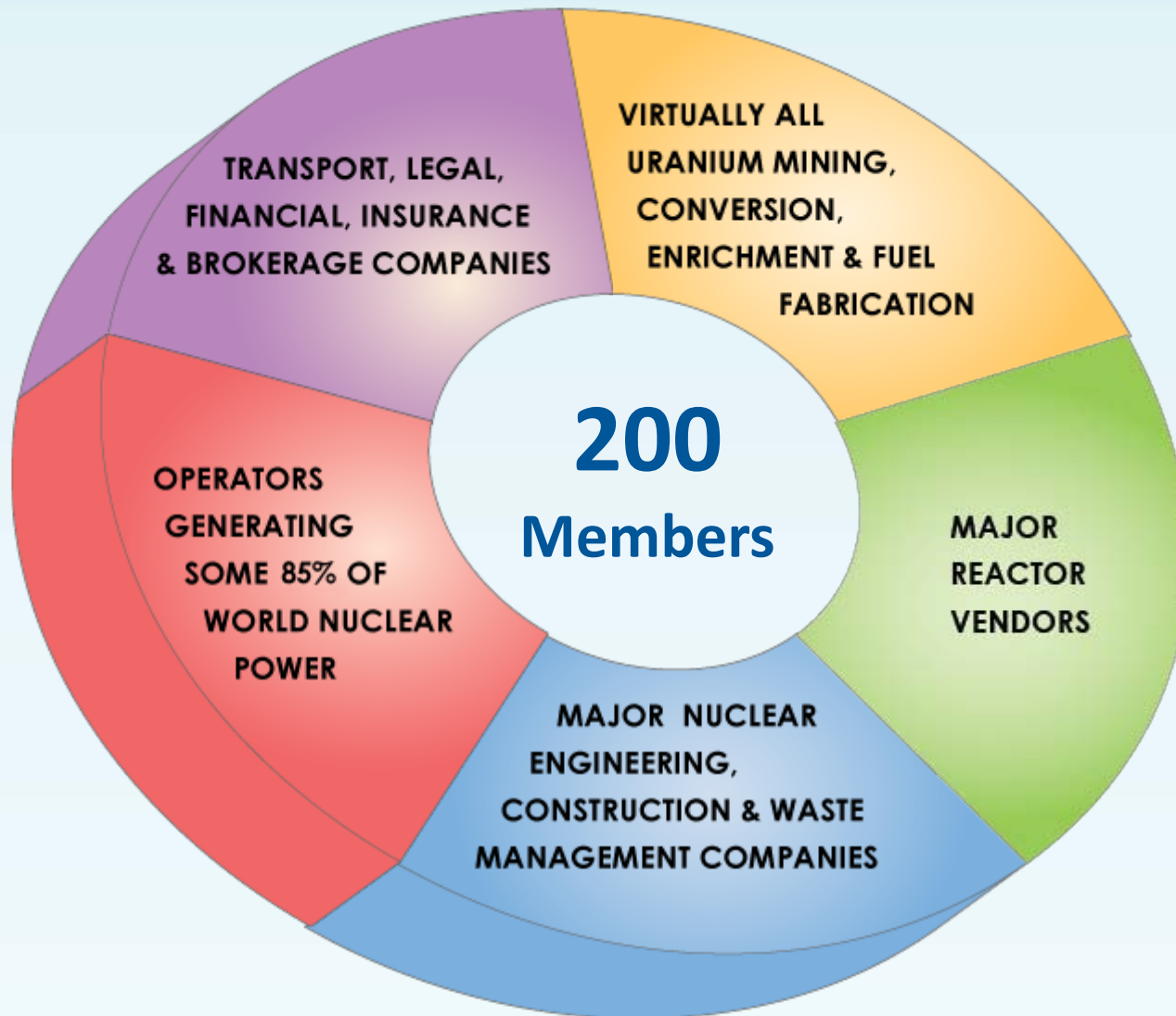
MPhil Nuclear  
Energy Lecture

Cambridge

17 January 2013



# World Nuclear Association



# WNA Roles & Activities



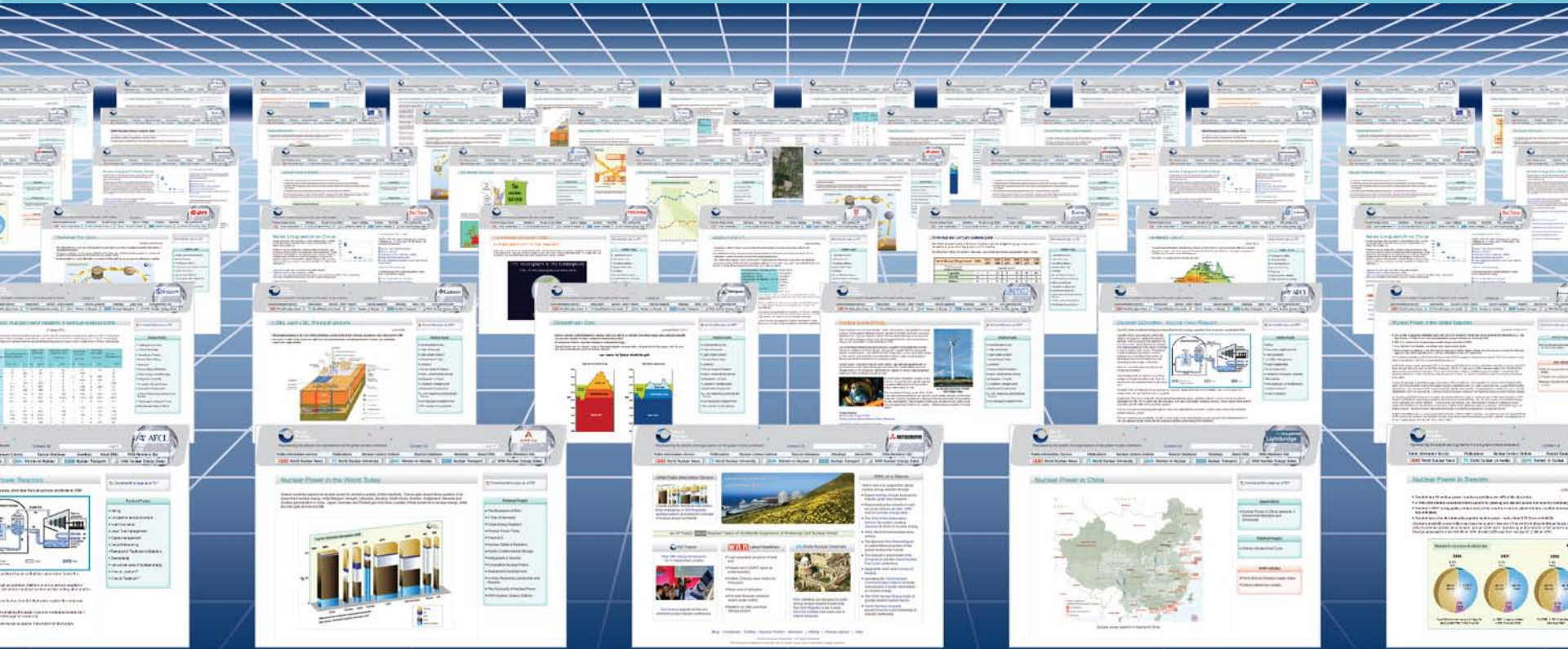
**4. Providing Public Information and News**

**3. Nuclear Fuel Market and Supply Chain**

**2. Enabling Industry Contacts and Cooperation**

**1. Representation in Key International Forums**

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## IAEA reviews Japan's nuclear restart

31 January 2012

**A team of international nuclear safety experts has reviewed procedure to confirm the safety of its nuclear plants as dire conditions grip the country's power industry.**

A mission to Japan lasting from 23 to 31 January saw a team of experts from the International Atomic Energy Agency (IAEA) at member states spend time with Japan's nuclear safety regulator which is conducting a two-stage assessment process to ensure plants have adequate protection against extreme external events.

While NISA continues its work to review the preliminary assessments supported by the Nuclear Safety Commission and the Japanese Energy Safety Organization, reactors are still closing one by one as mandatory safety inspections. Currently only three are in operation a potential operating fleet of 44, not counting the ten Fukushima and Daiichi units.

The preliminary report from the IAEA team to the Japanese government said NISA and nuclear operators had "promptly addressed" safety measures after the accident at Fukushima Daiichi. It offered a range of recommendations to NISA to ensure thorough and improvements in safety are made.



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## Privatisation of Russian state nuclear giant

02 February 2012

**Having spent five years combining its nuclear power, engineering and research enterprises into the single entity of Rosatom, the Russian government now sees privatisation of the firm as part of a plan for industrial modernisation.**

Rosatom is just one of several vertically integrated state holding companies Russia established to "discourage the decline of the more intellectual sectors of national industry" in the post-Soviet era, wrote Vladimir Putin in the *Vedomosti* newspaper on 30 January.

Currently in the role of prime minister, Putin served the maximum two terms as president from 2000 to 2008 and is now campaigning to return to that position in March 2012. He used the lengthy article to set out a range of government targets for Russia to develop its infrastructure, innovation and private enterprise while curbing corruption and improving the legal and investment environment for business.



Vladimir Putin

Speaking of sectors such as aerospace, shipbuilding and nuclear energy Putin wrote: "We had to consolidate those assets which were officially government-owned but managed disjointedly, and which had lost all links with their respective research and design centres."

Government efforts "were focused on restoring Russia's ability to compete in those sectors which involved only a few players on the global market," Putin wrote, emphasising that the "expansion of state capitalism" only occurred because there was no private initiative in those sectors. He stressed the scale of state action had no bearing on "our work to accumulate and restructure assets and get them ready for sale."



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## Approval for first nuclear new build in America

09 February 2012

**American safety regulators gave the go-ahead today for the construction of two new nuclear power reactors.**

The vote by the five-member commission brought to an end a regulatory process lasting almost four years that confirmed the safety of building two Westinghouse AP1000 reactors at the Vogtle site in Georgia. It is the first combined construction and operating licence issued by the US Nuclear Regulatory Commission (NRC).



Workers stand in the excavated and waterproofed space for Vogtle 3's reactor building (Image: Southern)

The review work of the NRC staff was celebrated by the commissioners in a confirmatory hearing today. Four commissioners voted to grant the licence, while chairman Gregory Jazcko abstained. He had wanted the recommendations developed in response to the Fukushima accident in Japan last year and said he "could not support issuing this licence as if Fukushima had not happened." The other commissioners spoke to Fukushima individually or collectively regarding the events of 11 March 2011 and the ensuing accident at Fukushima. She added that NRC staff did not recommend and did not support Jazcko's idea of a condition being attached to the licence. "In this case, we found a condition

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- Westinghouse secures AP1000 approval
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- Georgia PSC approves new Vogtle units

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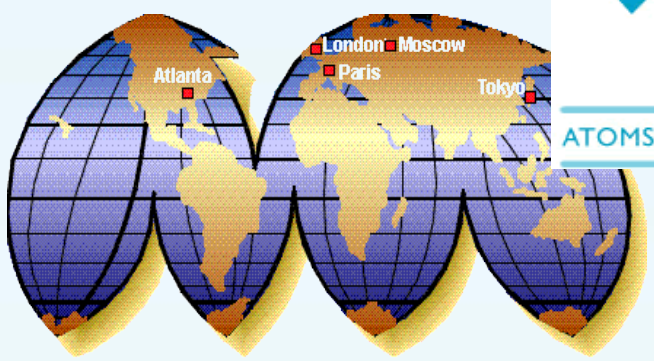
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**IAEA**



W A N O

ATOMS FOR SUSTAINABLE DEVELOPMENT



**World Nuclear Association**

# Daya Bay WNU class – July 2012

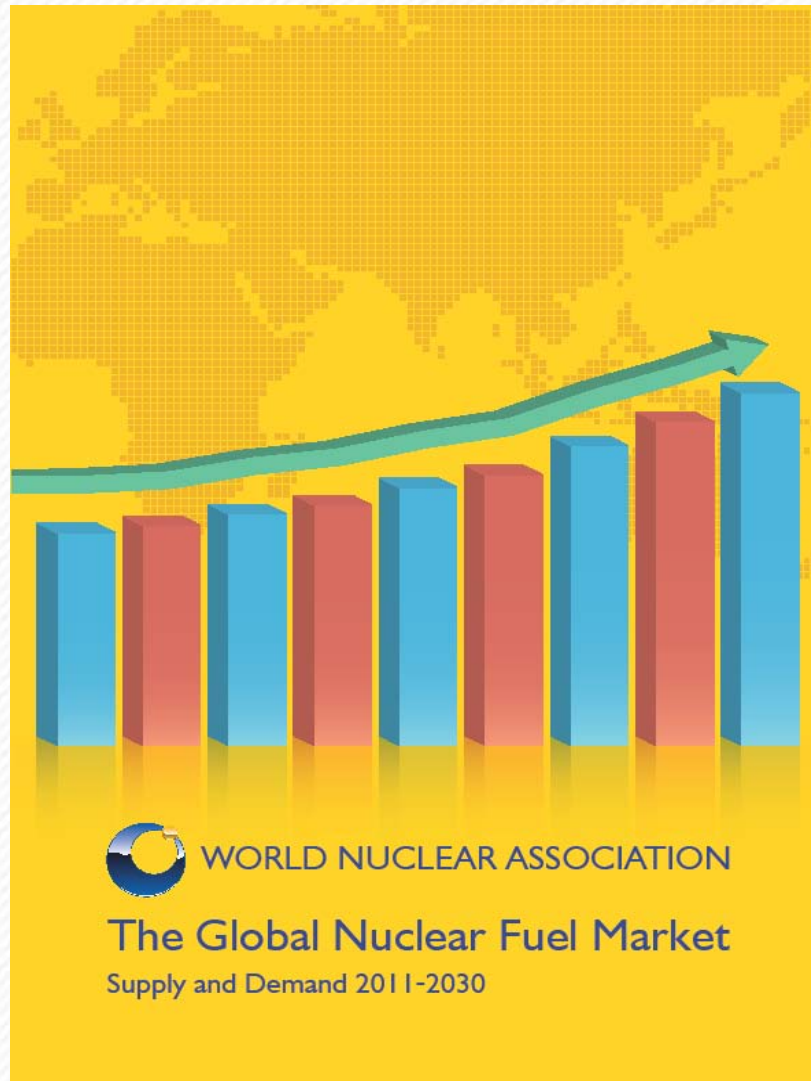


# Outline

- Overview of the fuel cycle and importance of fuel
- What determines the demand for nuclear fuel?
- Uranium
- Conversion
- Enrichment
- Fuel fabrication
- Nuclear fuel market

n.b. This presentation covers the commercial side of nuclear fuel  
- the technical side is a huge but different area!

# WNA Market Report 2011

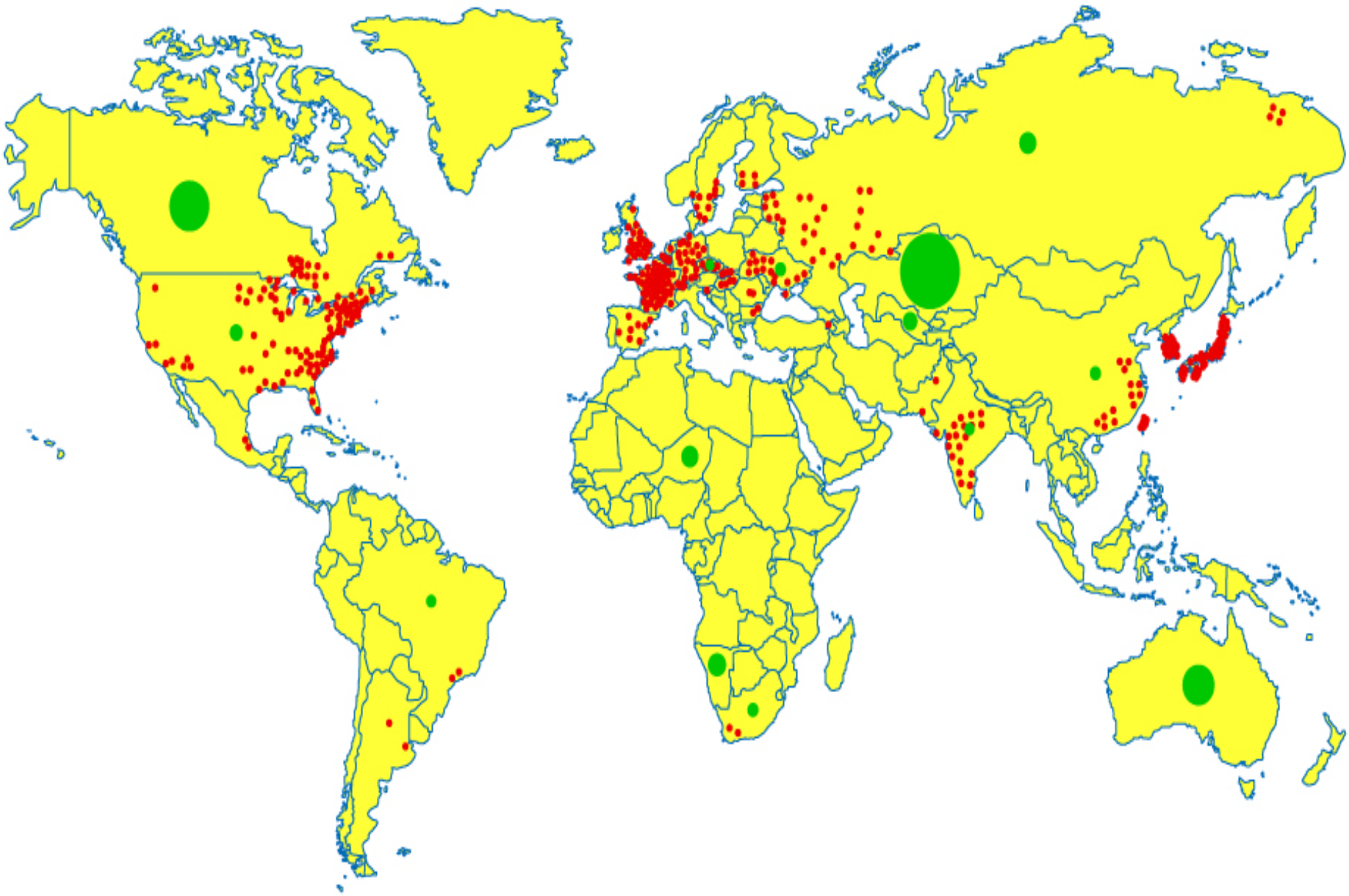


# WNA Market Report

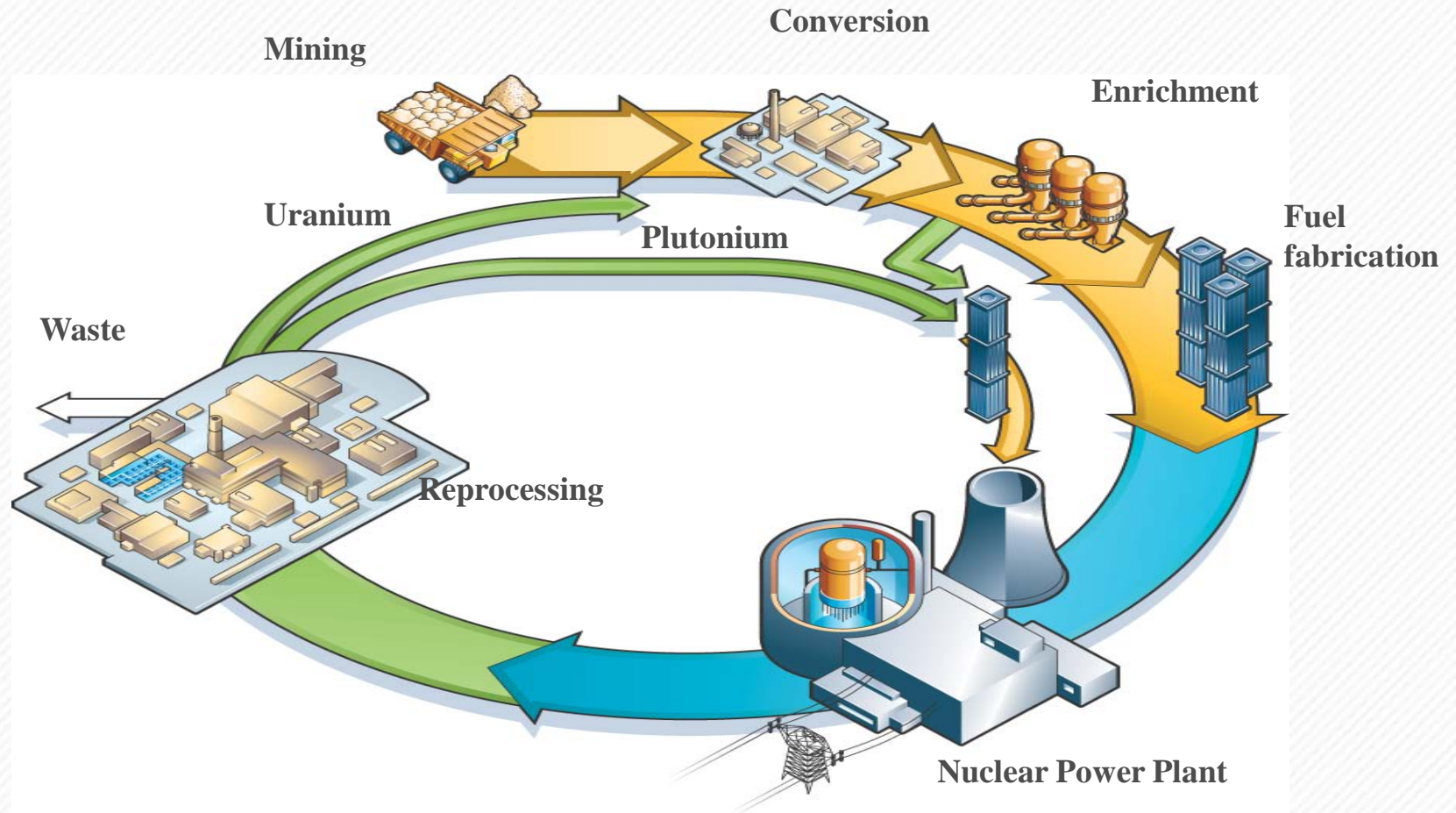
- This new report is the fifteenth in the series to be published since the foundation of the WNA (formerly Uranium Institute) in 1975.
- The report concentrates on the “front end” of the fuel cycle, from uranium mining to electricity generation, describing the supply and demand of
  - Natural uranium
  - Conversion
  - Enrichment
  - Fabrication
- This report maintains the forecasting period up to 2030.
- WNA Market report is produced mainly for the members of the WNA but it is widely used by many other sectors as nuclear energy getting more attention
- The report is highly appreciated by all sectors as it is based on the knowledge and opinion of the whole industry

# OVERVIEW OF THE FUEL CYCLE

# World Nuclear Power Reactors - with Uranium Sources



# The Nuclear Fuel Cycle - Closed



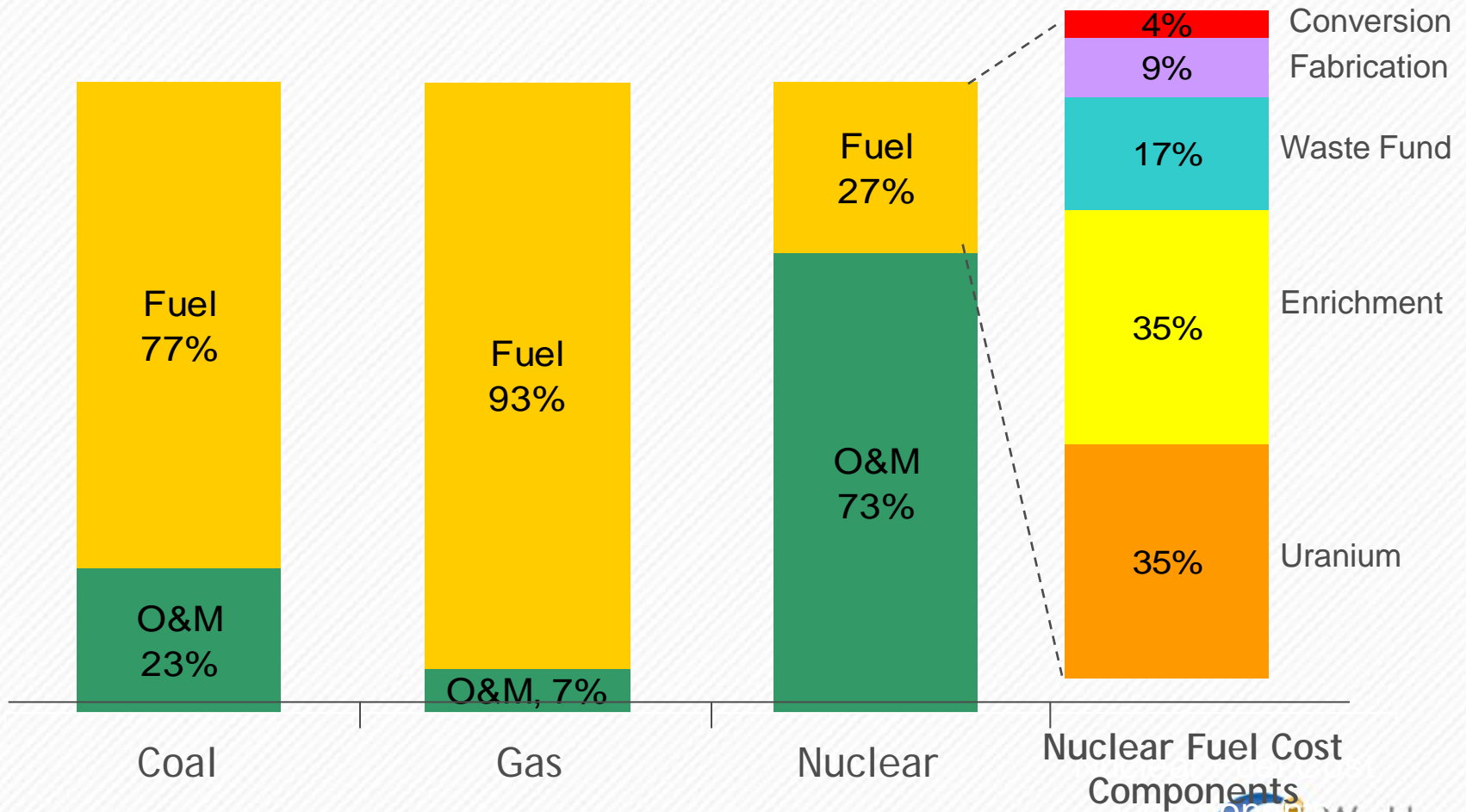
# Key aspects of fuel cycle

- Complexity!
- Specialisation of producers
- International aspects
- Trade rules & regulations
- Transport difficulties
- Recycling possibilities
- Historical production levels still relevant

# Relative Cost Structure of Power Generation

General shares	Nuclear	Gas CCGT	Coal
Investment	50-60%	15-20%	40-50%
O&M	20-35%	5-10%	15-25%
Fuel	15-20%	70-80%	35-40%

# Fuel as a Percentage of Electric Power Production Costs



Source: Global Energy Decisions; Energy Resources International, Inc.  
 Updated: 5/08



# Monthly Fuel Cost to U.S. Electric Utilities

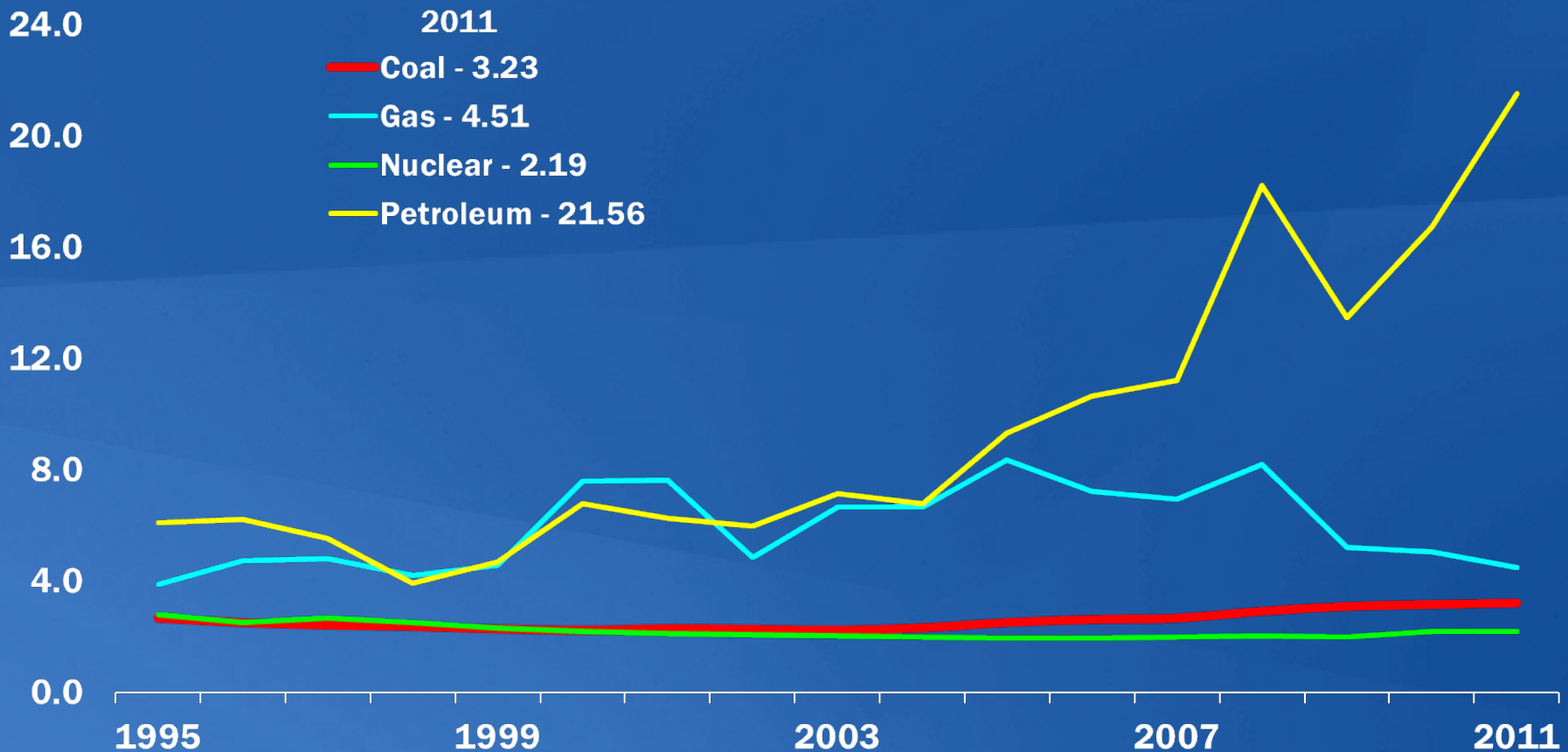
1995 – 2011, In 2011 cents per kilowatt-hour



Source: Ventyx Velocity Suite  
Updated: 5/12

# U.S. Electricity Production Costs

1995-2011, *In 2011 cents per kilowatt-hour*

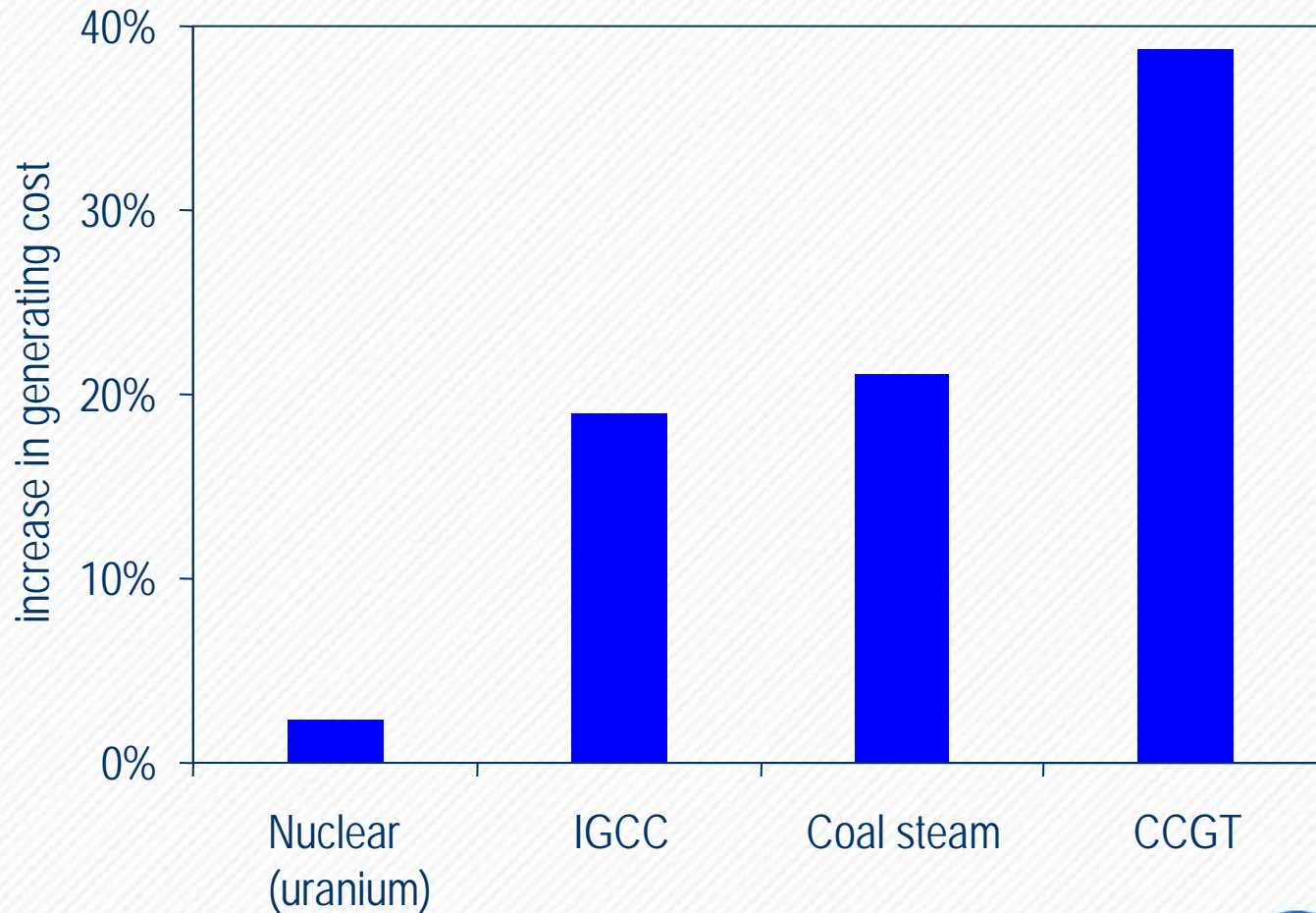


Production Costs = Operations and Maintenance Costs + Fuel Costs. Production costs do not include indirect costs and are based on FERC Form 1 filings submitted by regulated utilities. Production costs are modeled for utilities that are not regulated.



Source: Ventyx Velocity Suite  
Updated: 5/12

# Impact of 50% increase in fuel cost



Sources: IEA "World Energy Outlook 2006" - "Reference Scenario "

# Why is nuclear fuel important?

- Without it the reactor will not operate!
- Yet if it is so insignificant in nuclear economics, why are we bothering devoting a lot of time to it?
- But without cheap fuel, nuclear is dead economically. Everything else connected with a nuclear plant costs more!
- A paradox - fuel is essentially nuclear's biggest advantage, but potentially also its biggest drawback!

# Cost of 1 kg of enriched uranium

Uranium	9 kg U308	\$50 per lb	990
Conversion	7.6 kg U	\$13 per kg	99
Enrichment	7 SWU	\$150 per SWU	1050
Fabrication	1 kg	\$300 per kg	300
Total			\$2439

Need about 20 tonnes of enriched uranium for an average large reactor refuel, so cost will be about \$50 million

Total front end world market is now worth about \$25 billion annually

# DEMAND FOR NUCLEAR FUEL

# Demand for nuclear fuel

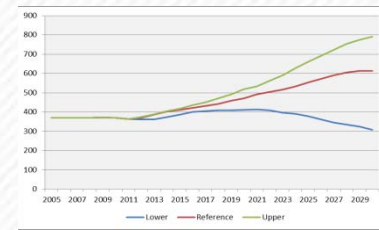
Depends on two factors

- Number and size of reactors in operation
- How they are run - load factors, enrichment level, burn-up and tails assay

# Nuclear generating capacity scenarios

- Country-level judgements
- Existing reactors - consideration of operating lives (technical, licensing and policy issues) - also power up-rates
- New reactors -
  - a) under construction
  - b) already within planning & licensing
  - c) proposed without firm commitment

# WNA scenario approach



- Due to the uncertainties in forecasting future nuclear generation, three scenarios are developed to cover the full range of outcomes.
- Generic assumptions underlie each scenario - on nuclear economics, public acceptance, impact of climate change debate and electricity market structure
  - Reference Scenario:
    - Improvements occur in the relative economics of nuclear power
    - Concerns about global warming continue
    - Gradual restructuring and liberalisation of electricity sector continue
    - The Fukushima accident has an impact in some countries, but most continue with their previous plans
    - Public acceptance problems for nuclear projects begin to diminish
  - Lower and Upper Scenarios:
    - More pessimistic and optimistic assumptions in these areas, compared with reference scenario
- No attempt is made to attach probabilities to each scenario

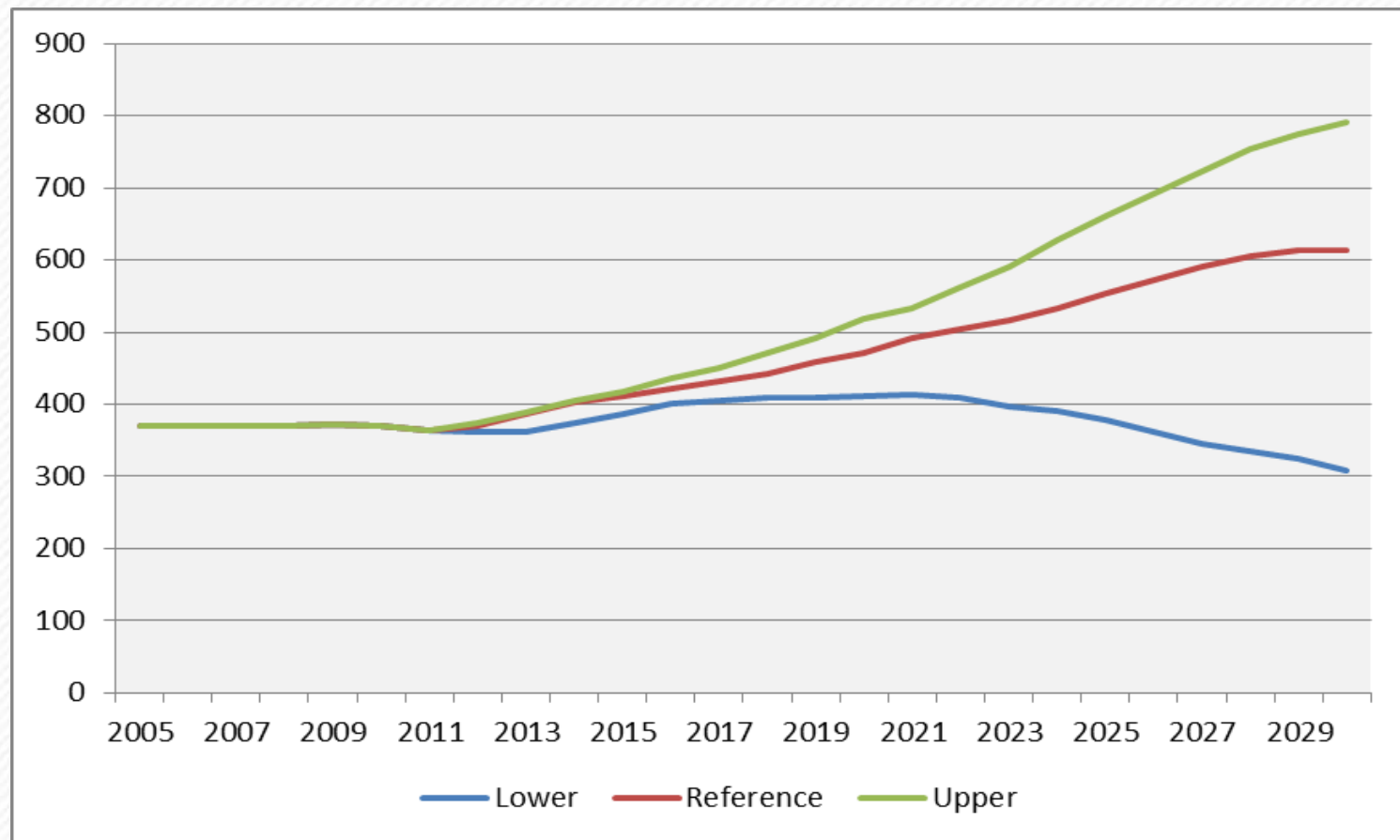
# Reflections on Fukushima - positive

- World energy situation is unchanged
- Lessons will be learned
- More attention will be paid to used fuel
- Beyond negative images, more attention and discussion of nuclear may benefit the industry
- More knowledge of radiation

# Reflections on Fukushima - negative

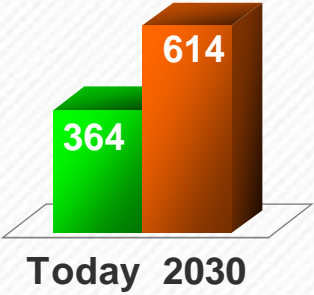
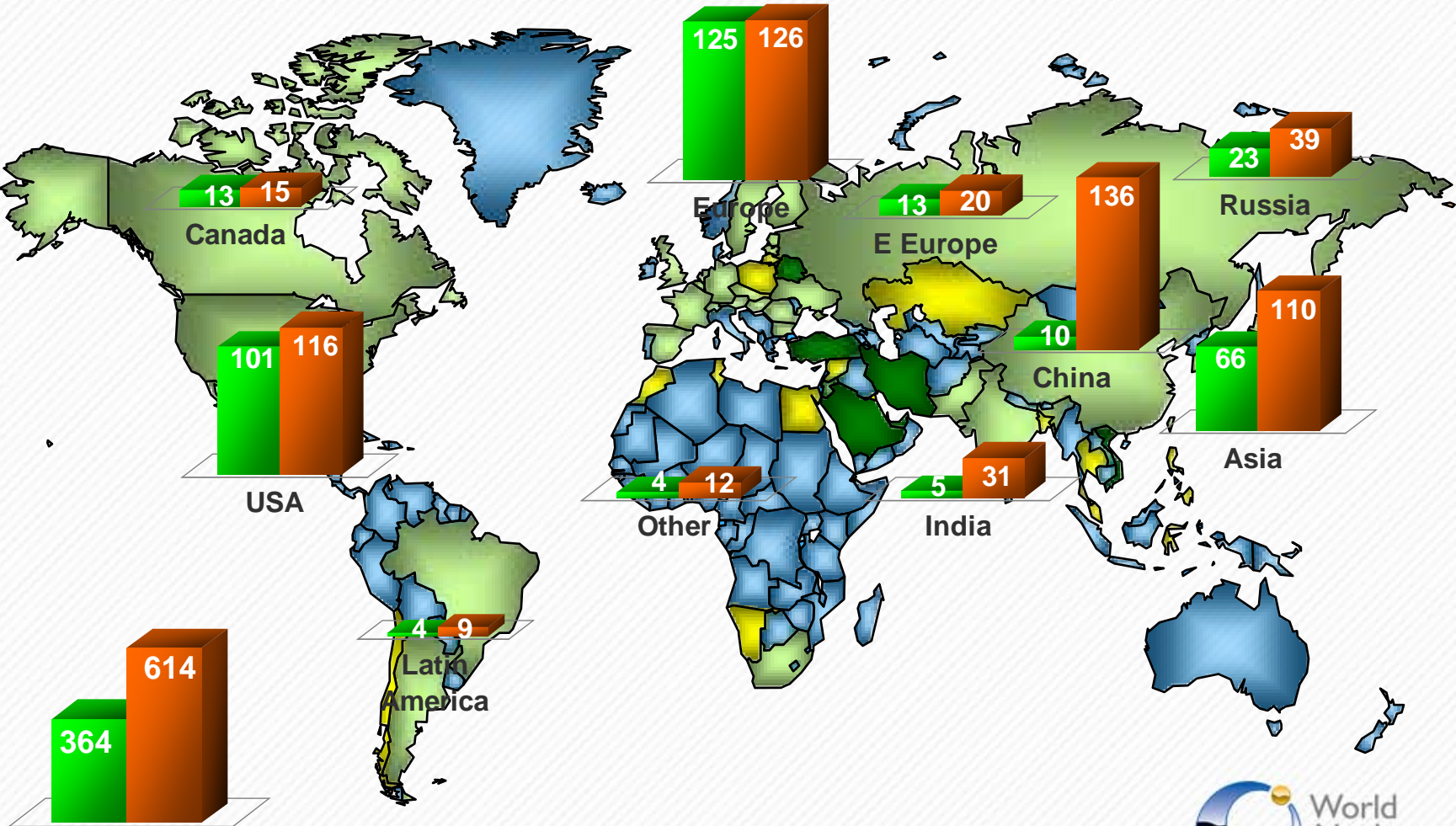
- More expense for operating plants
- Some will shut down earlier than expected
- New reactors maybe also become more expensive
- Harder to build plants in some countries where public opinion is difficult
- Story will “run and run” for months - especially the economic cost of evacuating people - more insurance?

# World Nuclear Generating Capacity, GWe



# Reference case to 2030, GWe

operating serious emerging

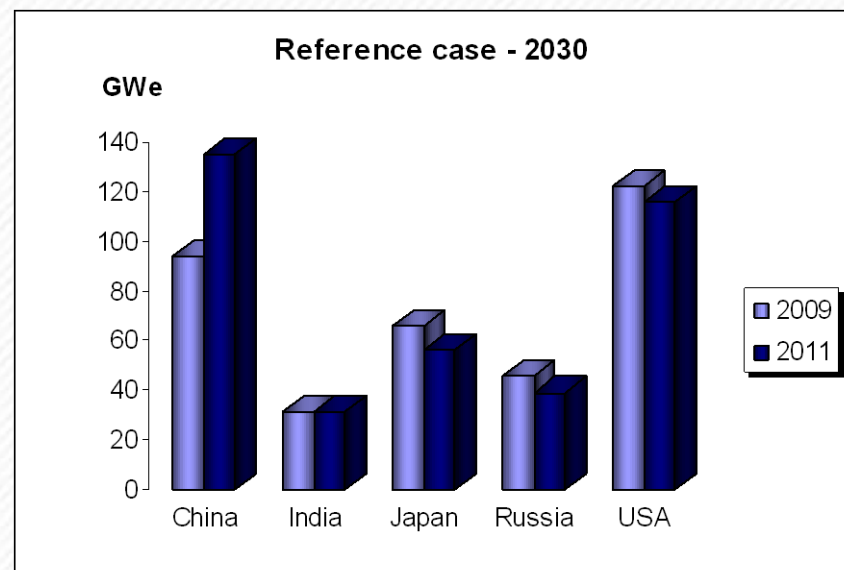
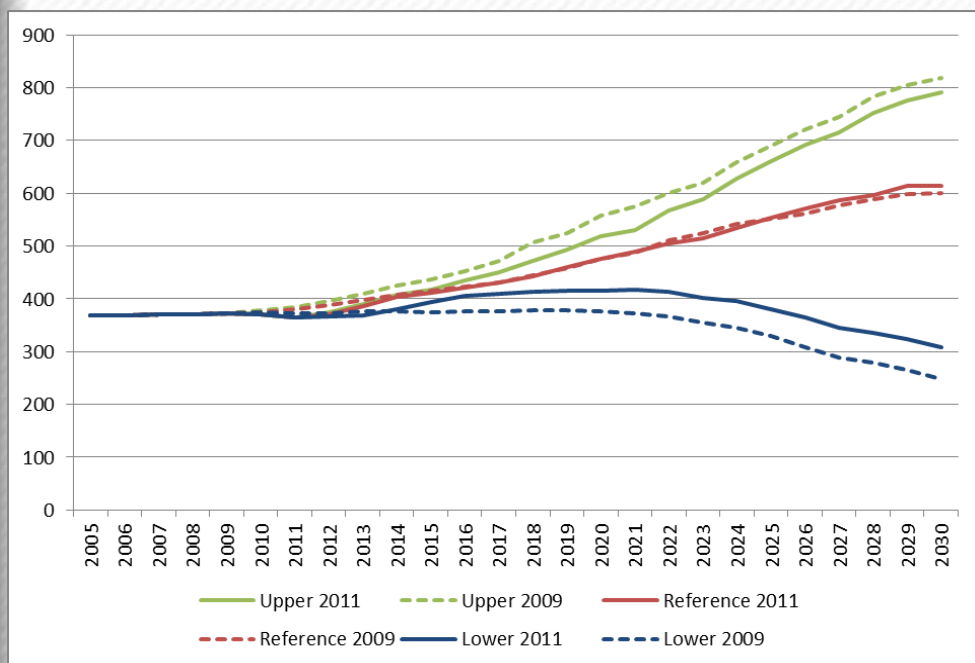


# Reference Case Reactors

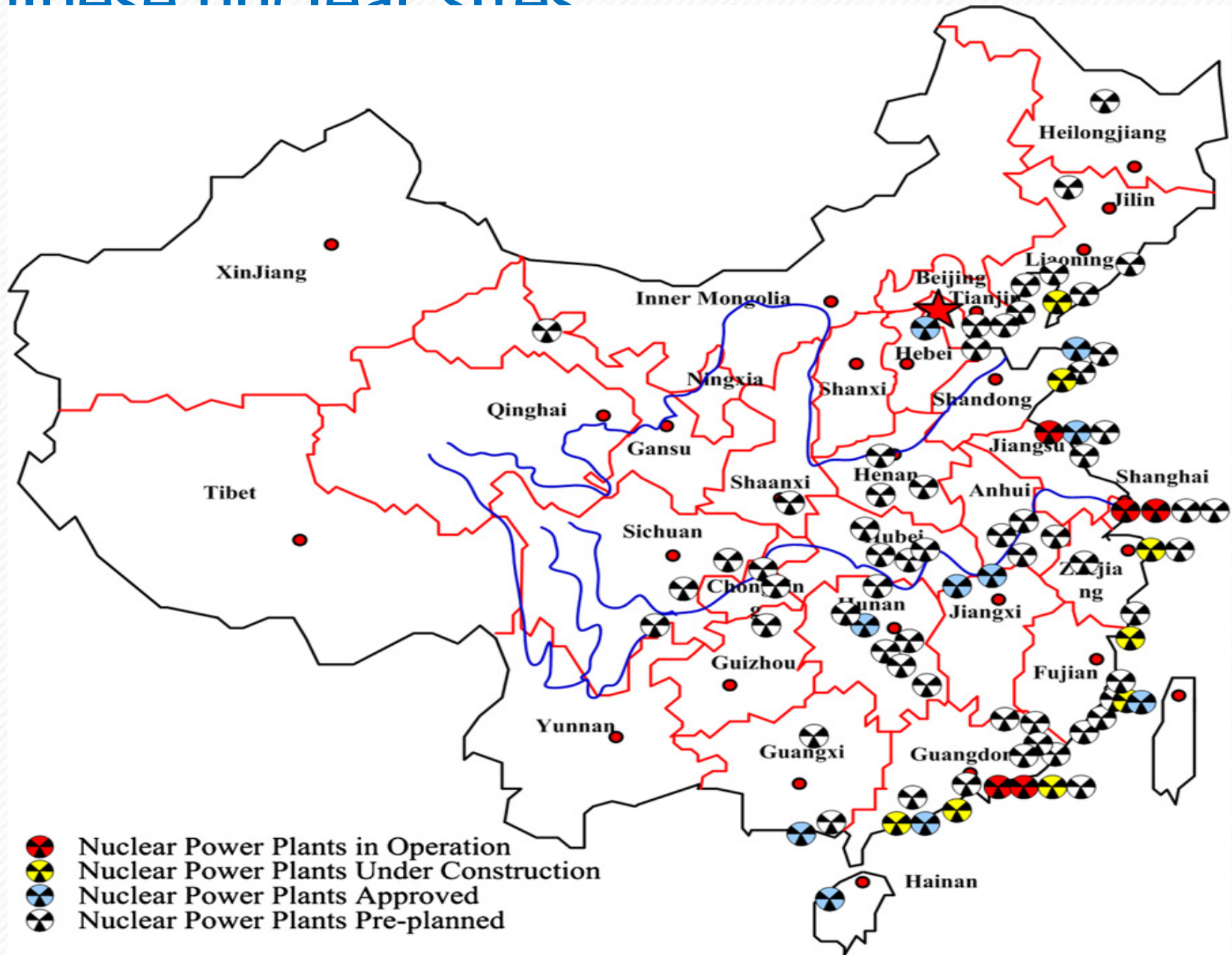
operating
  serious
  emerging

Regions	Operating 2009	New	Shut	Operating 2030	Change
Latin America	6	7	1	12	6
USA	104	30	32	102	-2
Europe	149	30	72	107	-42
Asia	79	41	16	104	25
Canada	18	4	3	19	1
Other	4	12	1	15	11
India	17	33	5	45	28
China	11	102	0	113	102
Russia	31	31	23	39	8
Eastern Europe	16	8	3	21	5
<b>Total</b>	<b>435</b>	<b>298</b>	<b>156</b>	<b>577</b>	<b>142</b>

# World Nuclear Generating Capacity, 2011 vs 2009 Report



# Chinese nuclear sites



# Chinese reactors under construction

- 4 x AP1000 at Sanmen and Haiyang
- 2 x EPR at Taishan
- 19 x CPR-1000 at 6 sites
- 2 x CNP-600 at Changjiang
- 1 x VVER-1000 at Tianwan
- 1 x HTR-PM at Shidaowan

Total - 29 units, 30 GWe

# Forecasting reactor requirements



GWe - Nuclear generating capacity



MS Excel-based spreadsheet model  
Fuel cycle and reactor operating factors



tU - Uranium, conversion and  
enrichment requirements

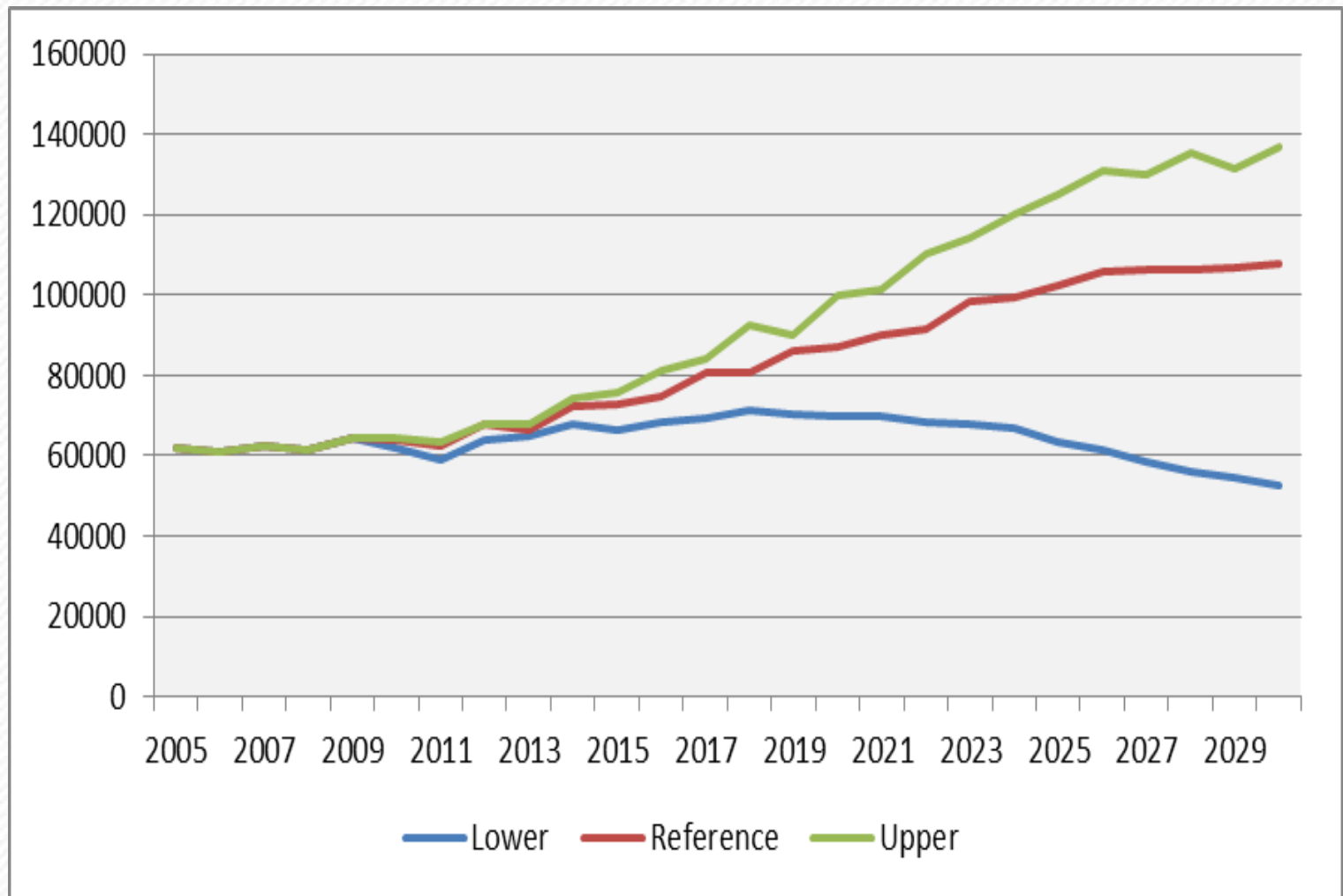
# Fuel cycle & reactor operating factors

Capacity factors	10% worldwide increase in 1990s - still rising
Enrichment level	rising slowly - up to 5% U-235
Fuel burn-up	now rising above 50 GWd/tU
Tails assay	Possible substitution between uranium and enrichment, depending on relative prices

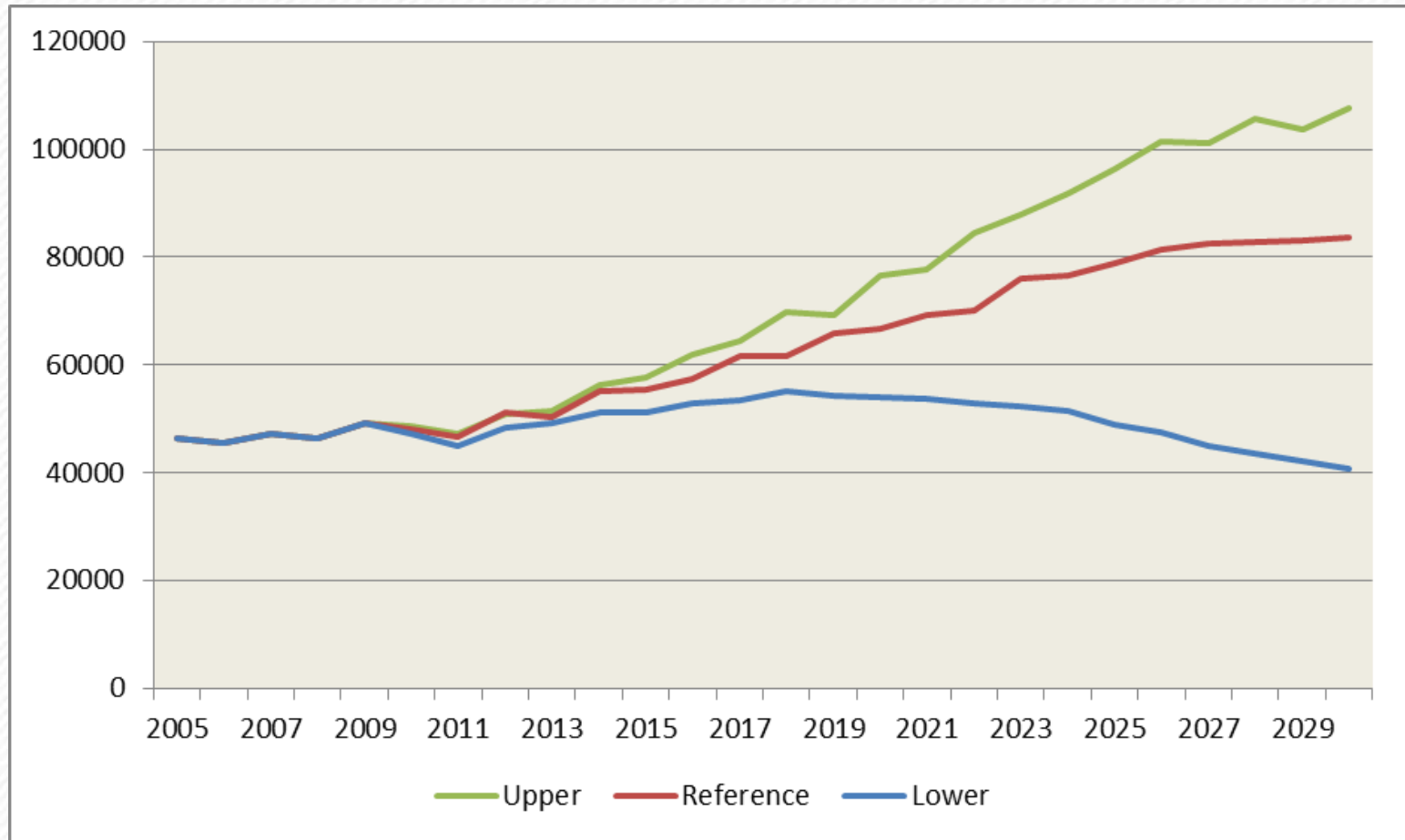
# Importance of the tails assay

- Reactor operators require enriched uranium and can achieve this by many combinations of uranium and enrichment
- Relatively high enrichment input means lower tails assay (waste stream from the enrichment plant)
- Essentially an economic decision - relative price of U and SWU
  
- Optimal tails assay - 0.30%-0.35% until 2003-04, now below 0.25%
- 2009 Market Report - 0.15% for Russian-origin reactors, 0.25% for Western-origin
- 2011 Market Report - 0.22% for all reactors

# World Uranium Requirements, tU



# World Enrichment Requirements, 000's SWU



# URANIUM

# Uranium geology

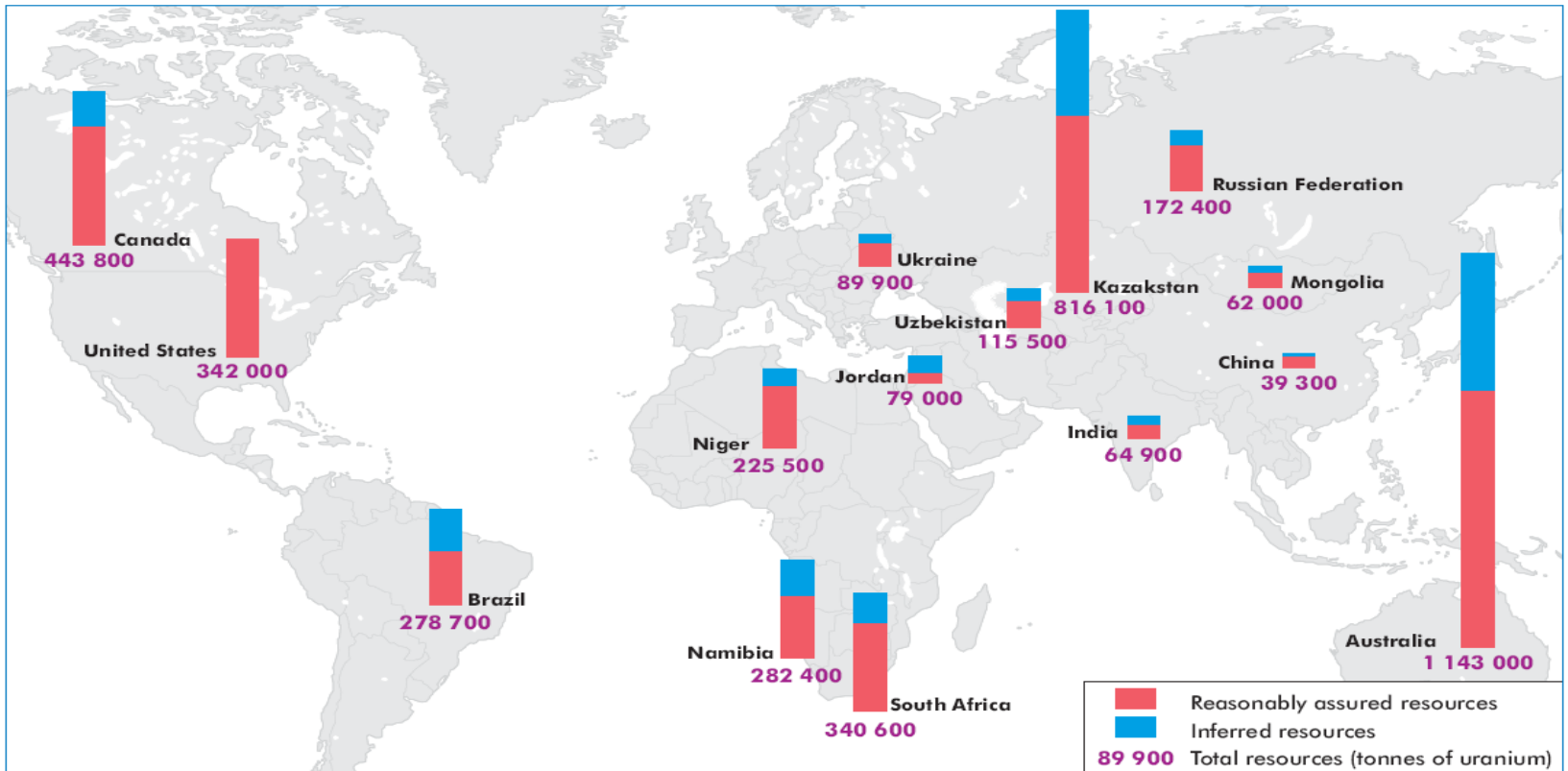
- Found in several different types of deposits
- 0.1% grade enough for mining today
- Average concentration in Earth's crust 2.8 ppm
- Phosphates
- Trace amounts in sea water
- Uranium is by no means scarce

WNA Position Statement

Can Uranium Supplies  
Sustain the Global  
Nuclear Renaissance?



# Global distribution of uranium resources



# Low cost (<\$80/kg) uranium reserves, 000 tonnes U

Australia	714
Kazakhstan	344
Canada	329
South Africa	206
Russia	172
Brazil	157
Namibia	145
Ukraine	127
USA	99
Others	155
Total	2438

# World uranium production 2011, tU

Kazakhstan	19451
Canada	9145
Australia	5983
Niger	4351
Namibia	3258
Russia	2993
Uzbekistan	2500
USA	1537
Others	4276
Total	53494

# Top 10 companies producing uranium, 2011, tU

KazAtomProm	8884
Areva	8790
Cameco	8630
ARMZ-Uranium One	7088
Rio Tinto	4061
BHP Billiton	3353
Navoi	2500
Paladin	2282
Others	7906
Total	53494

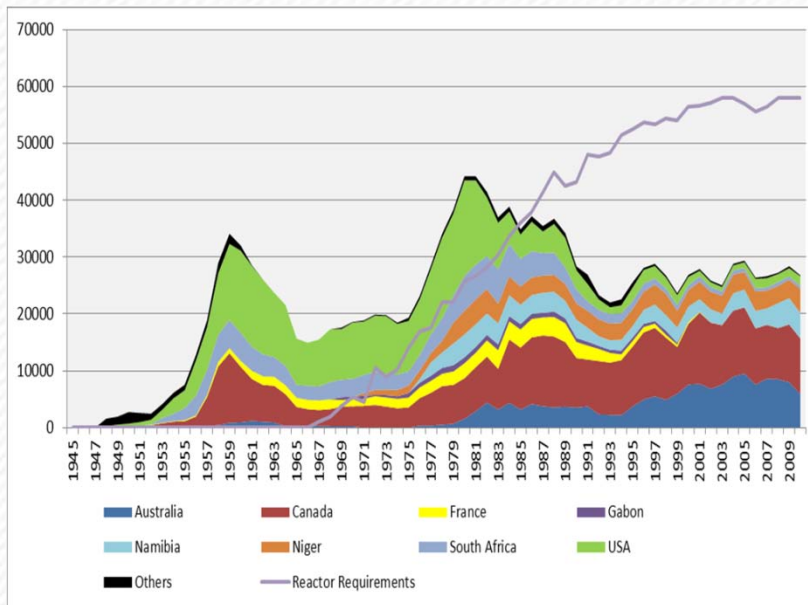
# Top 10 uranium mines 2011 tonnes U

McArthur River	7686
Olympic Dam	3353
Arlit	2726
Tortkuduk	2608
Ranger	2240
Krasnokamensk	2191
Karatau	2175
Rossing	1822
Inkai	1602
South Inkai	1548

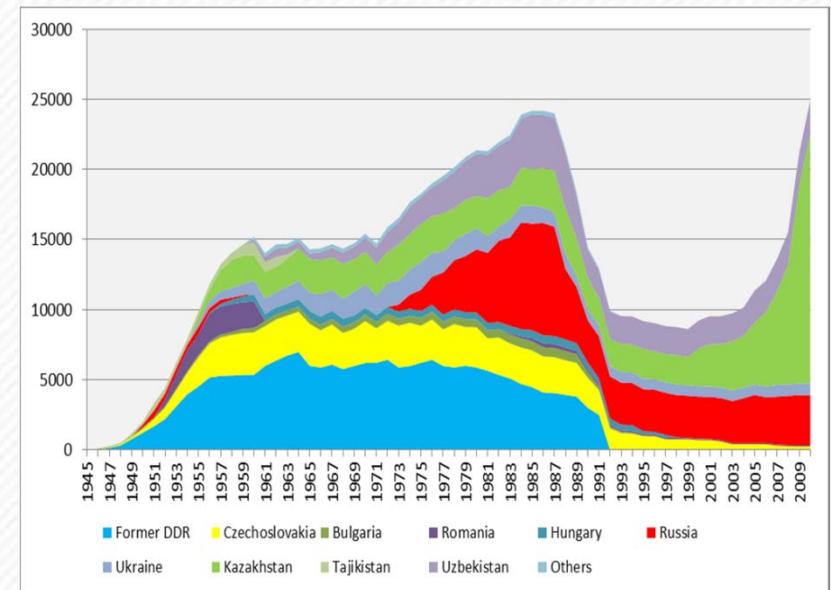
# Uranium production by mining method, 2011

Conventional underground	30%
Conventional open pit	17%
In situ leaching (ISL)	45%
By-product	7%
Total	100%

# Historical uranium production



Western world total 1,520 ths.tU



USSR and Eastern Europe- 928 ths.t U

Since 1945	Ths. tU
Produced	2 449
Consumed	1 933
Stockpiled	516

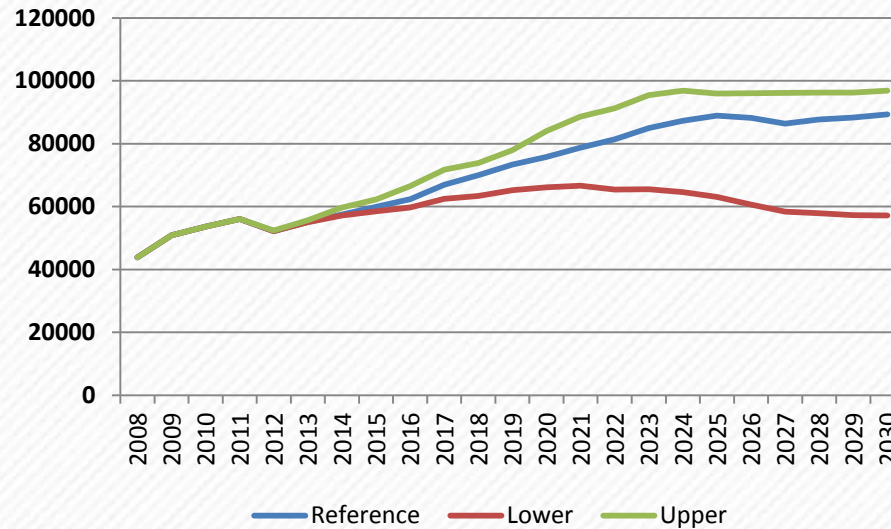
Production was substantially ahead of reactor requirements until 1985, but has since fallen below. Since 1985, requirements have exceeded production by approximately 450,000 tU. The difference was covered by inventories and other secondary sources

# Future uranium production

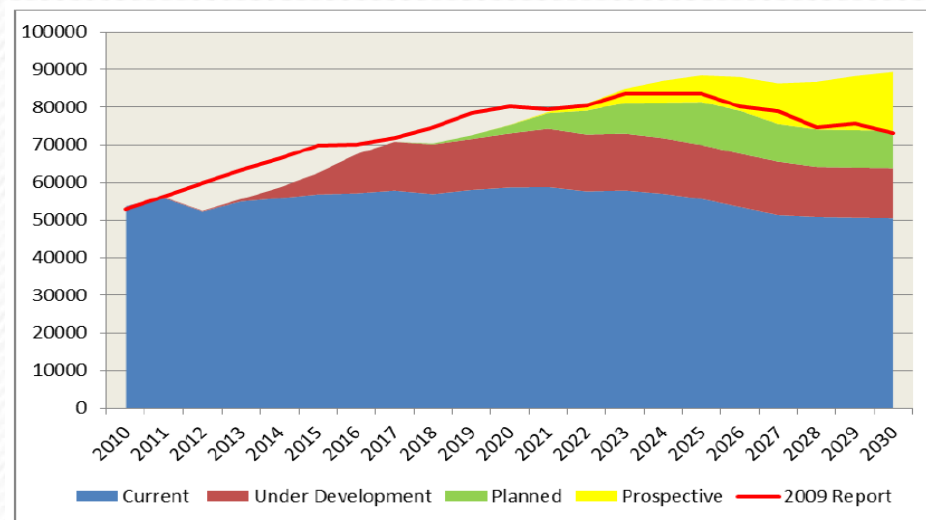
- Must now increase sharply to (a) cover rising demand and (b) diminishing secondary supplies
- Recent trend has been for increased dominance by a small number of major producing companies and countries
- Kazakhstan and Africa to lead expansion
- More exploration now taking place - stimulated by higher prices
- Over 200 “junior” uranium companies have suddenly appeared
- Some will eventually produce but how many?

# Anticipated uranium production through 2030

## Scenarios for prospective uranium production, tU



## Reference scenario prospective production, tU



# Secondary supplies

- Can be regarded as previous uranium production, held off the market for an extended period
- An important element in nuclear fuel supply
- Ex-military materials
- Commercial inventories
- MOX and RepU fuel

# Mixed oxide fuel (MOX) and reprocessed uranium (RepU)

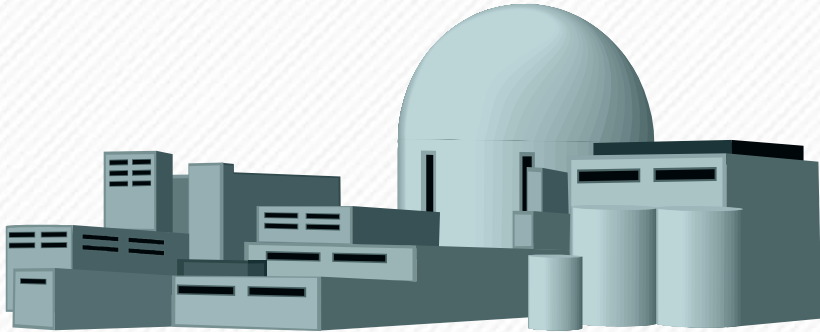
- Reprocessing plants separate uranium and plutonium from used fuel
- RepU is re-enriched by centrifuges or blending to produce fresh fuel
- Extracted plutonium is introduced as the primary fissile element in MOX fuel
- Major reprocessing plants in France and UK with one nearing completion in Japan
- Russian system has always relied more on a closed fuel cycle

# Will the future look like this?

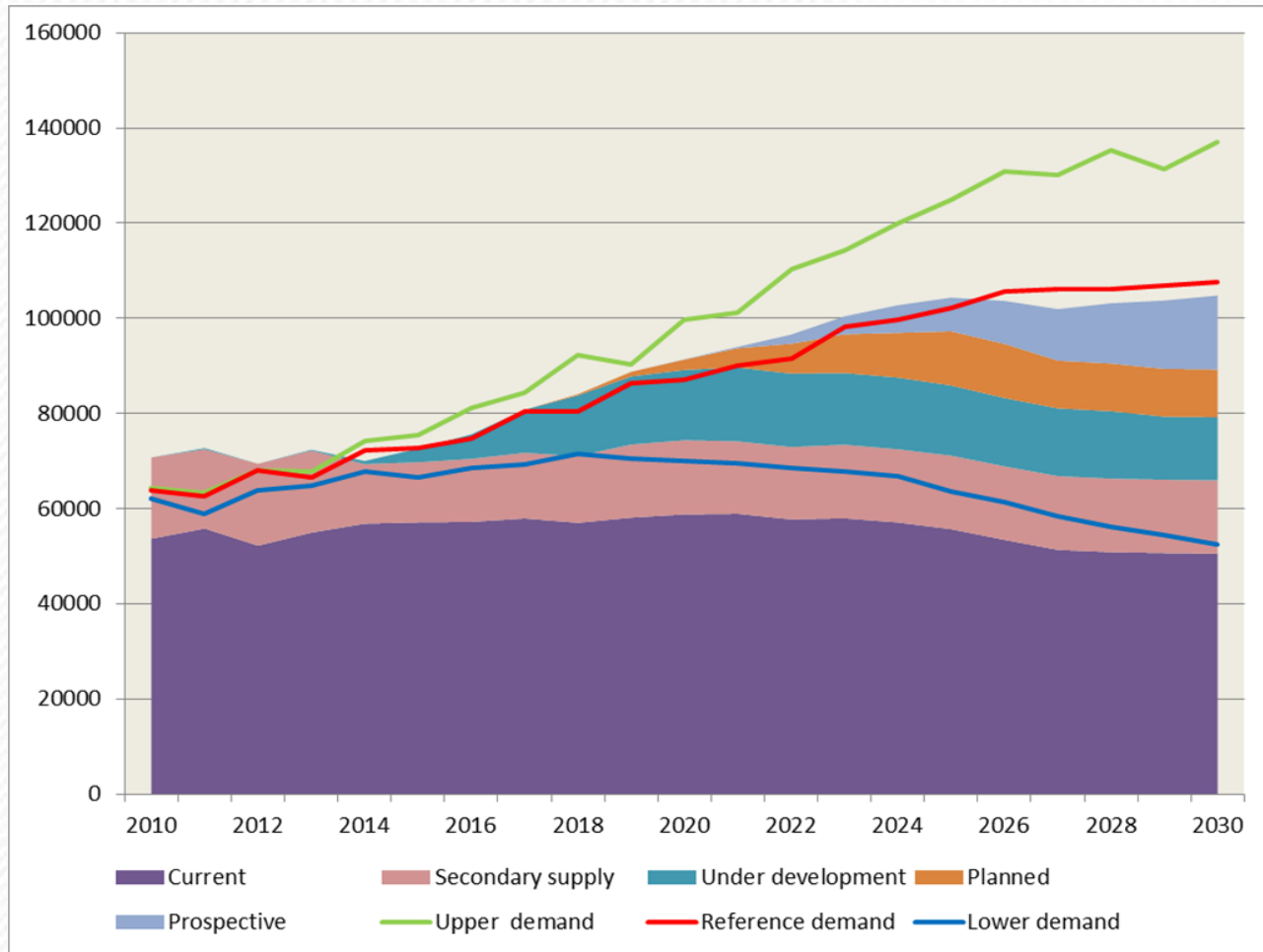
Help,  
we need  
more!



Sorry,  
we are out  
of material.



# Reference case U supply demand balance, tU

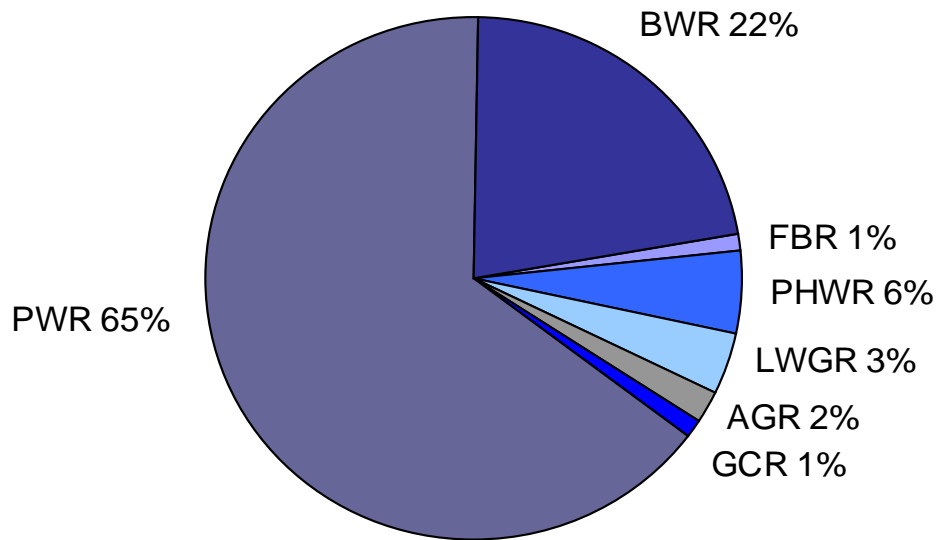


# Conclusions

- Uranium market has sound supply to 2020 but meeting demand becomes more challenging thereafter, unless the lower scenario is accurate
- Primary uranium supply needs to rise sharply to meet rising market demand
- Secondary supplies will remain important

# CONVERSION

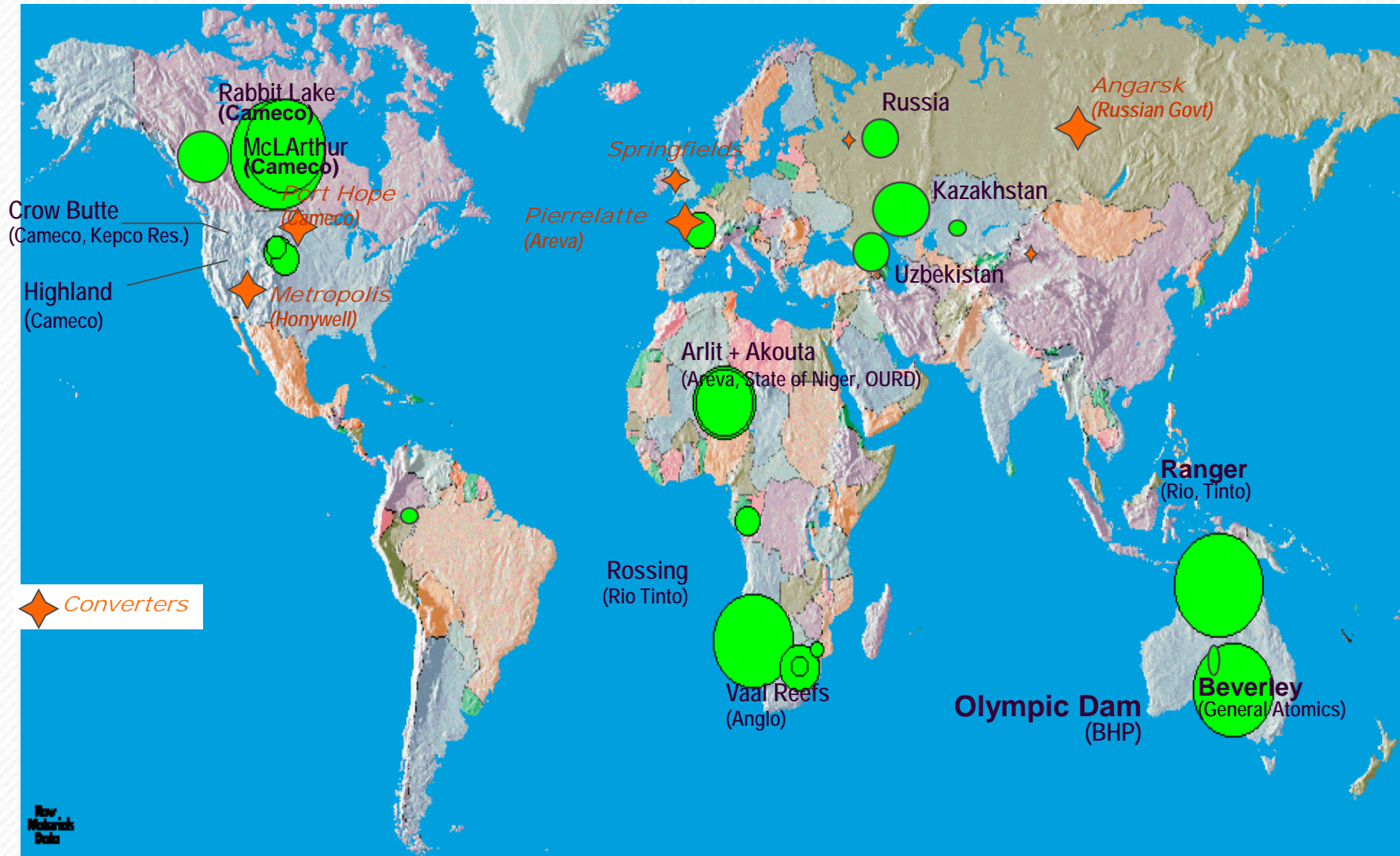
# Reactors by type



# Conversion - basics

- Enrichment for light water reactors requires conversion of uranium to  $UF_6$
- CANDU reactors require direct conversion to  $UO_2$
- 4 major  $UF_6$  conversion suppliers - Cameco, Comurhex (Areva), ConverDyn and Rosatom
- $UO_2$  conversion by Cameco and domestic suppliers in Argentina, China, India and Romania

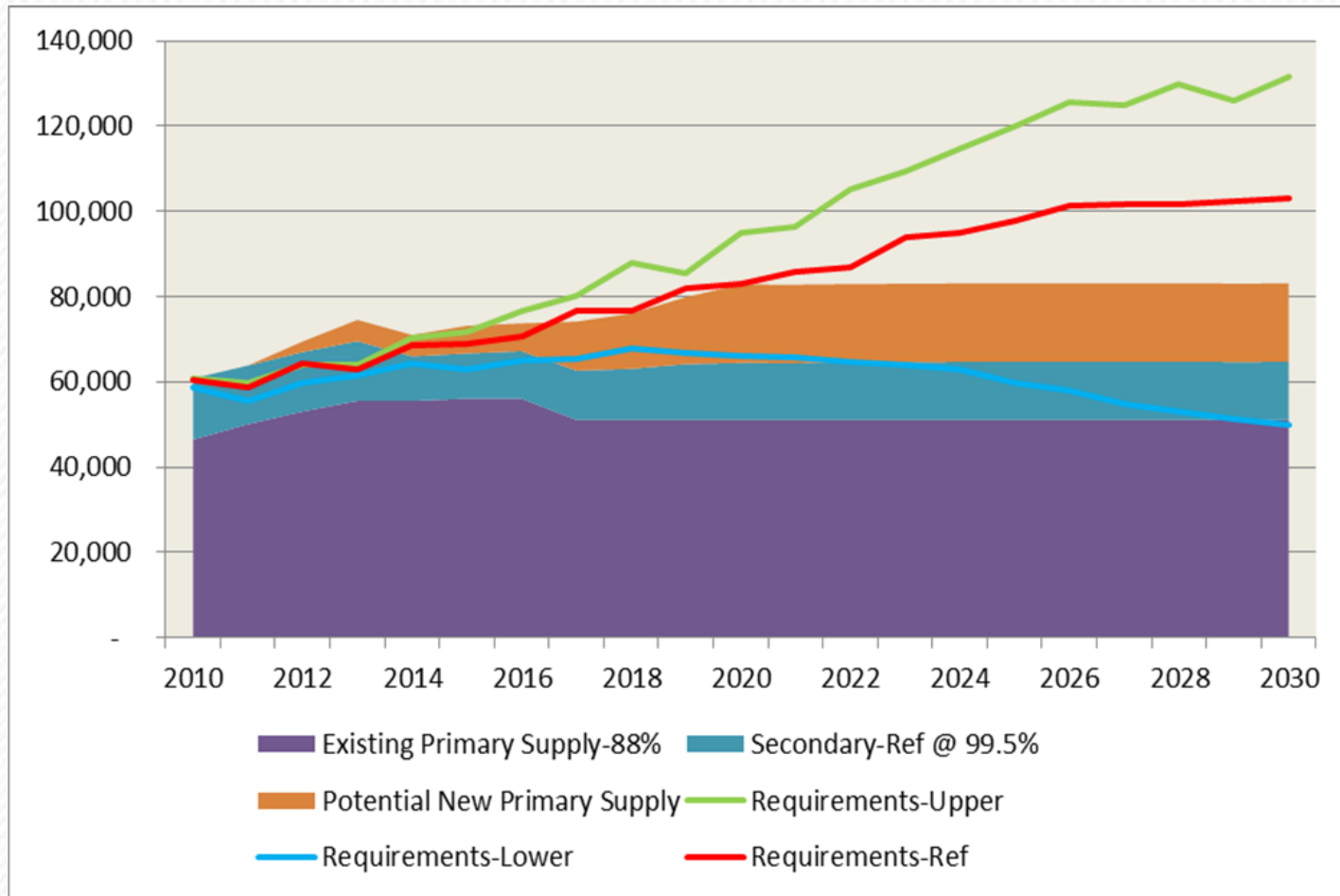
# Uranium operations & conversion facilities



# UF<sub>6</sub> conversion capacity, tU

Cameco	Canada	12,500
COMURHEX	France	14,500
CNNC	China	3,000
ConverDyn	USA	15,000
Rosatom	Russia	25,000
Westinghouse	UK	6,000
IPEN	Brazil	90
Total - nameplate capacity		76,090

# Reference case world conversion supply and demand

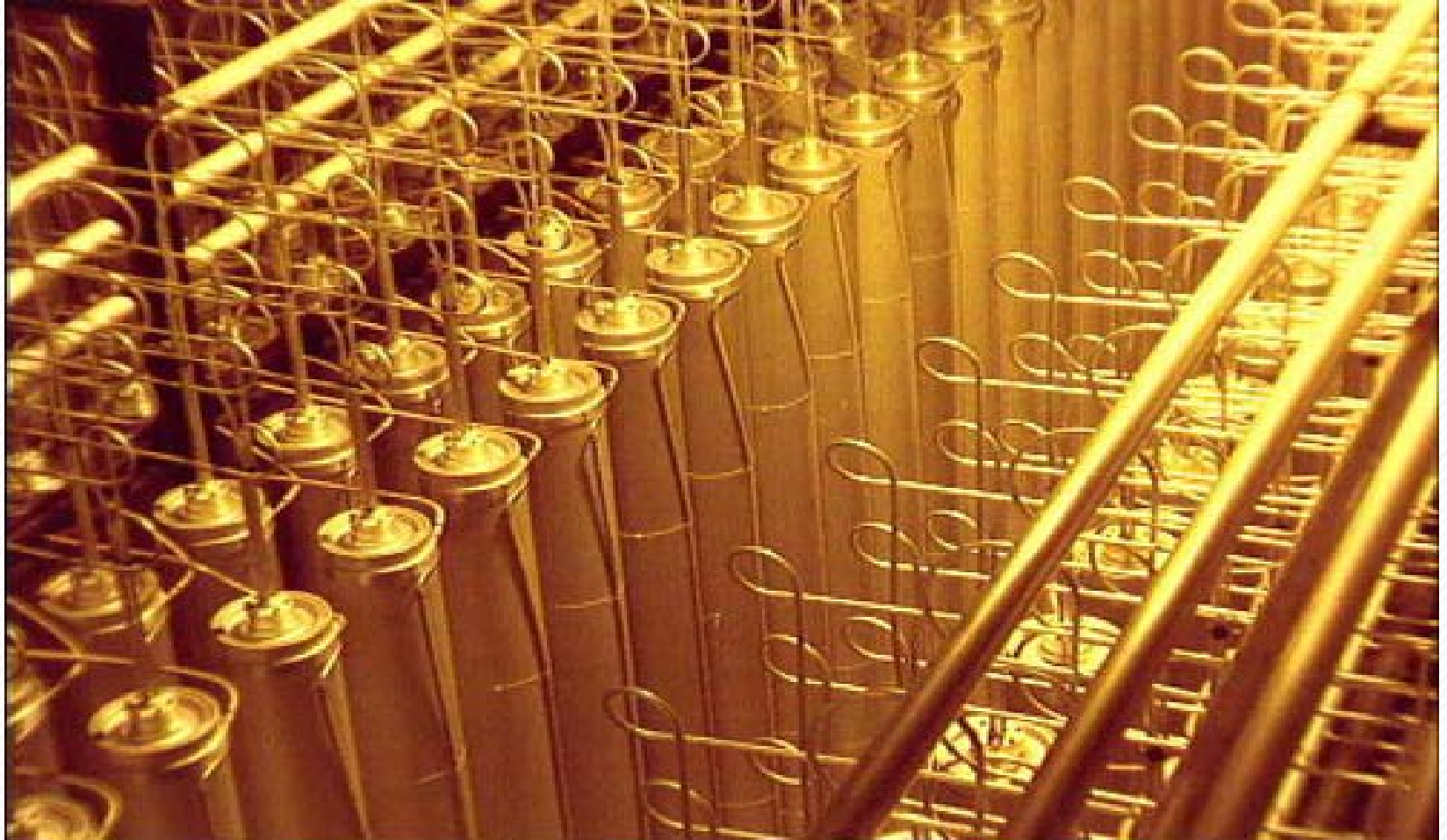


# ENRICHMENT

# Enrichment - basics

- 90% of current power reactors need fuel where the U-235 isotope is above the natural 0.71% (typically 3-5%)
- Two main technologies - gaseous diffusion and centrifuges
- Investment in laser enrichment so far unrewarded by commercial application
- Large front-end expense for utilities
- Effort expended is measured in separative work units (SWUs)
- Significant part of capacity was historically developed for military requirements

# Centrifuges



# What is a SWU?

- A unit unique to the nuclear industry
- A measure of the quantity of work or effort necessary to create a quantity of enriched uranium from natural uranium
- A complex unit - detailed mathematical formulae
- Given the huge electricity input in gas diffusion enrichment plants, the SWU could effectively be taken as the electricity required to separate the two isotopes

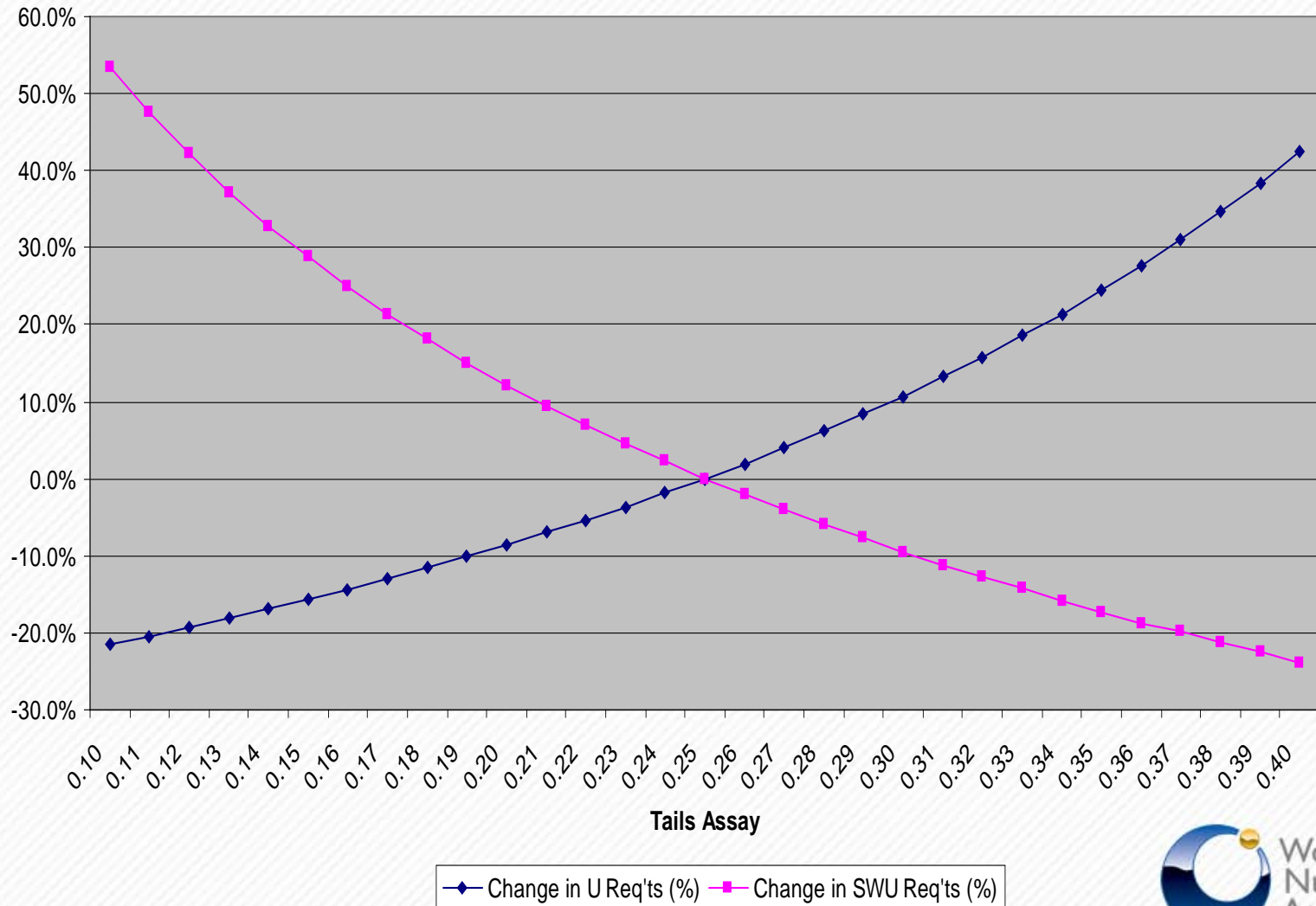
# Enrichment - supply

- Four large suppliers of primary enrichment services - USEC, Eurodif (Areva), Urenco and Rosatom
- USEC and Eurodif have used gas diffusion
- Urenco and Rosatom already use centrifuges
- JNFL and CNNC also primary suppliers
- Heavy current investment in new centrifuge plants by USEC and Urenco in US and by Eurodif in France (and eventually US too)
- Will SILEX as a laser technology prove commercially viable?

# Enrichment capacities, 000 SWUs

CNNC	China	1,300
Eurodif	France	3,000
JNFL	Japan	150
Rosatom	Russia	25,000
Urenco	Europe	13,000
	USA	1,500
USEC	USA	7,000
Others		100
Total - nameplate capacity		51,050

# Percentage variation in U & SWU requirements with tails assay



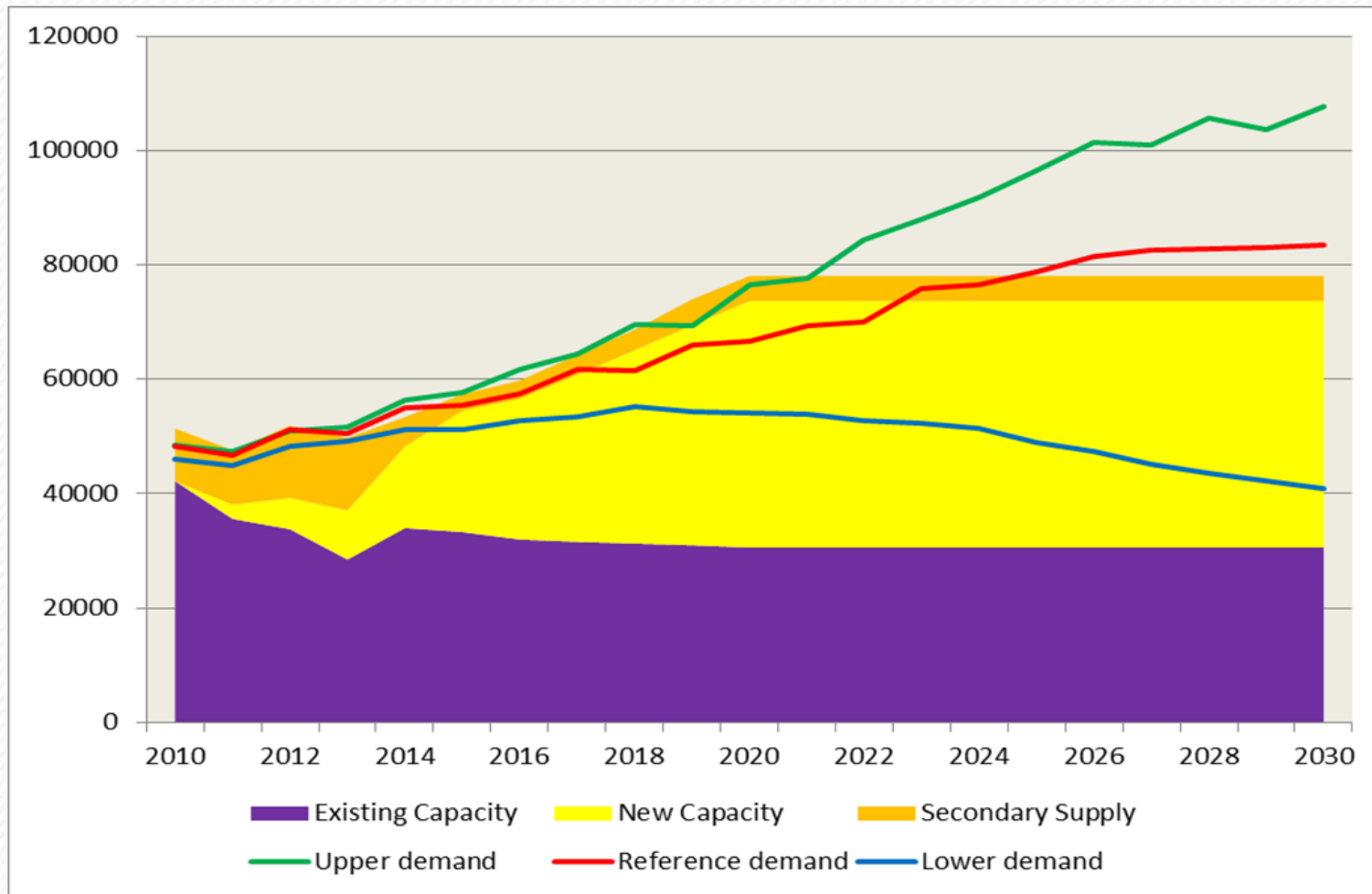
# Depleted uranium

- Over 1.6 million tonnes in storage throughout the world
- Volume increasing by 50,000 tonnes per annum
- Use in diluting HEU
- Possibility of re-enrichment to form new reactor fuel
- Very minor non-nuclear uses owing to density

# Enrichment - current issues

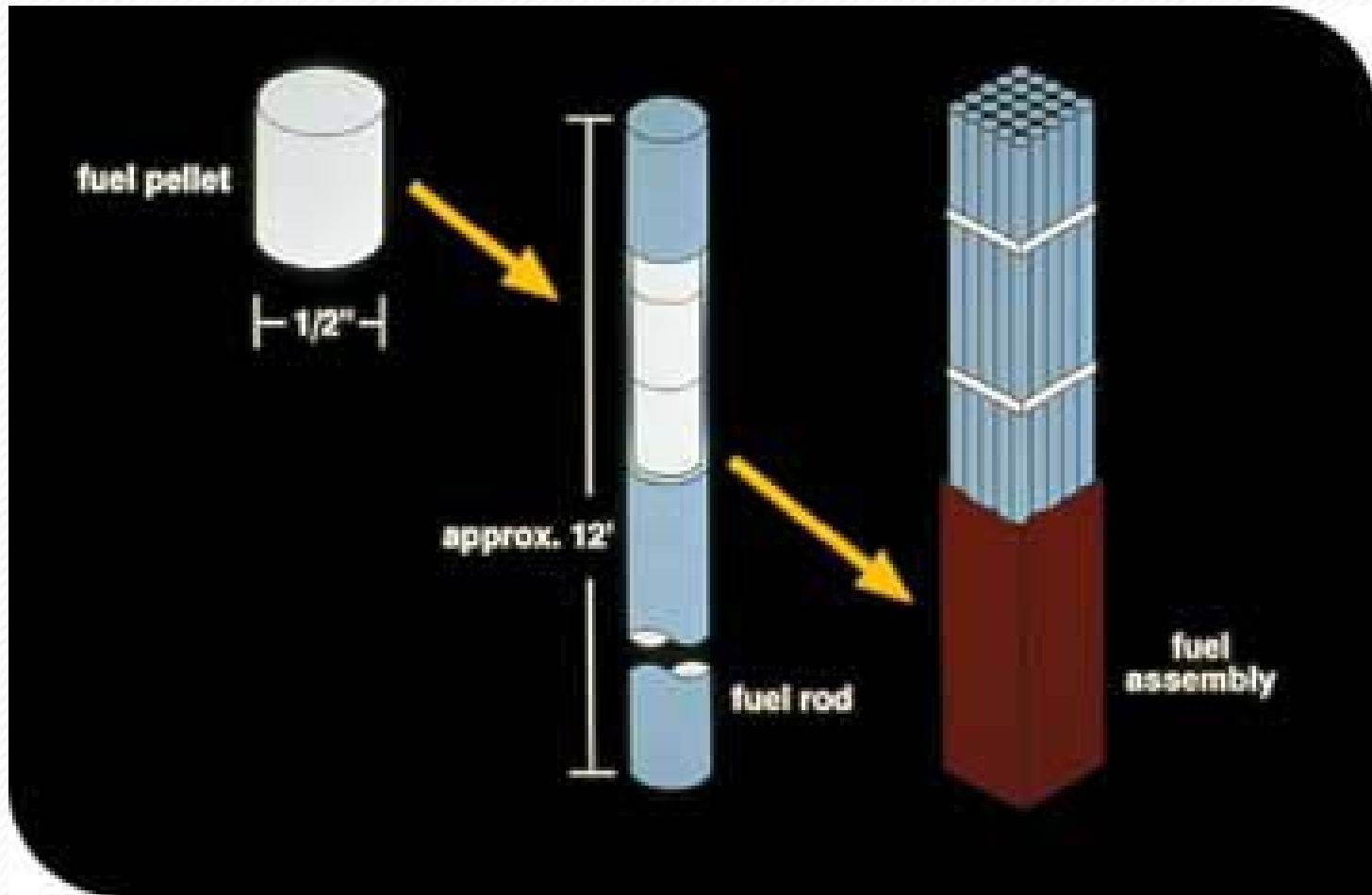
- Acute proliferation issues surround this area of the fuel cycle - similar to reprocessing of used fuel
- Proposals for “regional fuel cycle centres”
- Significant dependence on down-blended Russian HEU - half of SWUs supplied in US in recent years
- Difficulties of access to large Russia capacity for Western reactor operators
- Some capacity is today devoted to re-enrichment of depleted uranium (“tails”)

# World reference enrichment capacities supply and demand



# FUEL FABRICATION

# Fuel fabrication - process



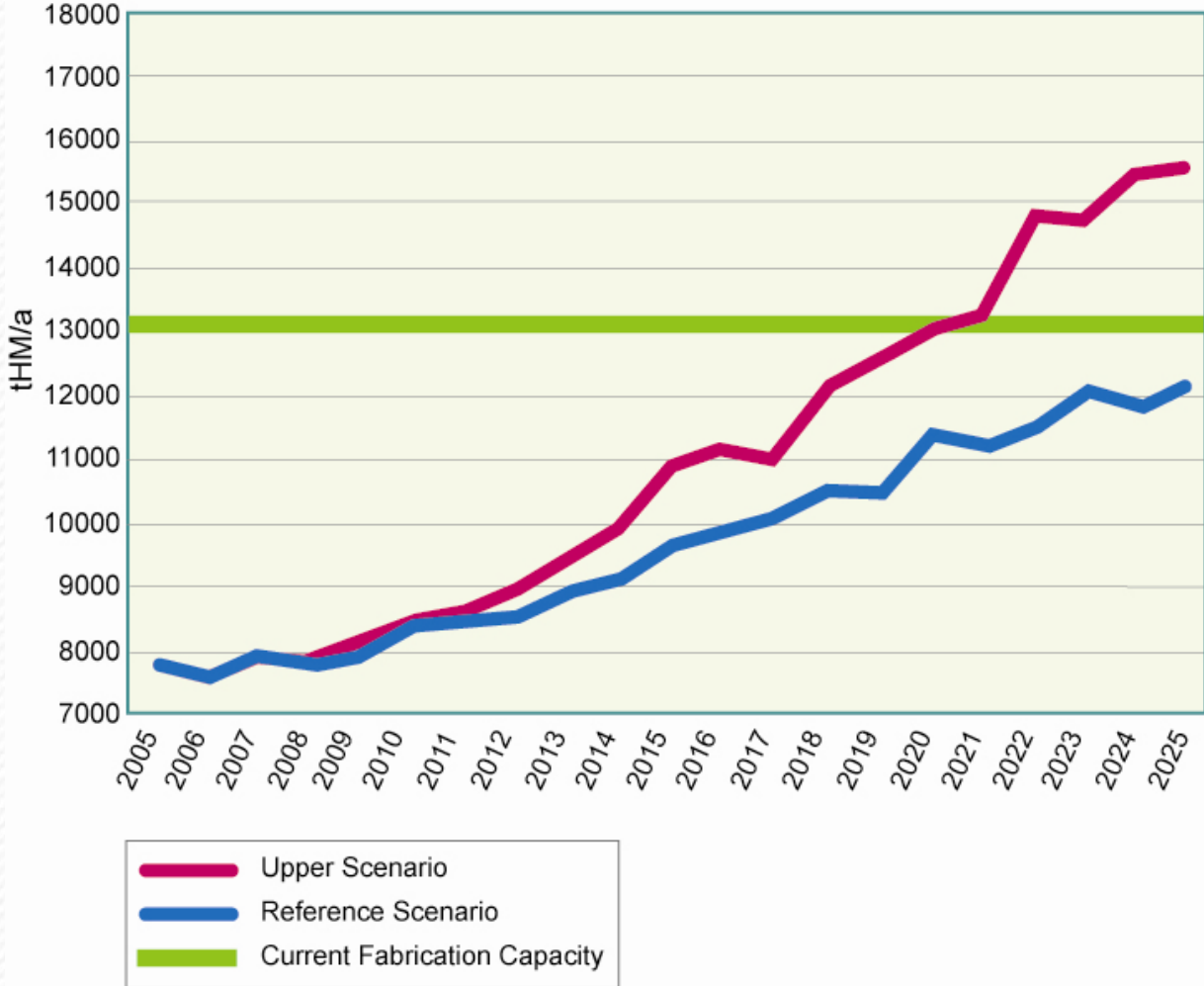
# UO<sub>2</sub> powder, pellet and fuel assembly



# Fuel fabrication

- Fundamentally different to uranium, conversion and enrichment - not a bulk commodity item and “fungible” - but a “high tech” product/service
- Annual requirements for LWR fuel fabrication is about 7,000 tonnes of heavy metal (enriched U)
- Annual requirements for CANDUS and other reactor types are 2,000-3,000 tU per annum
- Production much more “localised” than other areas of fuel cycle
- “Big boys are Areva NP, Toshiba-Westinghouse, GE-Hitachi and TVEL
- Important smaller suppliers - CNNC, JNFL, KNFC, ENUSA

# Fabrication supply/demand



# Outlook

- Supply of nuclear fuels will be sufficient to meet demand, even if requirements rise sharply
- But heavy investment will be needed to improve fuel cycle infrastructure
- Over the long-term, new reactor designs, much more efficient in their use of fuel, may fundamentally change the nature of the fuel market

# NUCLEAR FUEL MARKET

# Features of nuclear fuel market

- Fuel is not generally bought in its fabricated form - rather the reactor operator buys uranium and conversion, enrichment and fuel fabrication services separately
- Many contracts are very long term
- Reactors are only refuelled once per year - buyers don't need to be in the market all the time
- Fuel can be easily stored - inventories can play an important part in the market
- Spot market is largely an outlet for smoothing out unforeseen blips in supply and demand
- Spot market prices relevant to many longer term contracts

# Market structure

- Few participants
- Small number of transactions - illiquid
- Not transparent - most deals highly confidential
- Data on prices limited - spot market quotations, estimates of contract prices and historic series

# Spot uranium prices - current



# A new era for the uranium market?

- It has not functioned well in the recent past
- Dramatic price increase since 2003 - supply very tight
- Gradual move back towards long-term contracts rather than “spot” transactions
- Both reactor operators and mining companies have similar time perspectives - both long-term
- Market transparency issue
- Will quotations on NYMEX and similar help?
- Participants are conservative in their practices

# Concluding issues for uranium market

- How to secure more liquidity and transparency?
- Reforming what we have.....or a revolution?
- Buyers will do all they can to economise on uranium
- Prices must become connected with costs at some point
- Risk of price collapse cutting off necessary investments in new capacity