MEEN 40090: Energy Systems & Climate Change
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Nuclear Energy (5)

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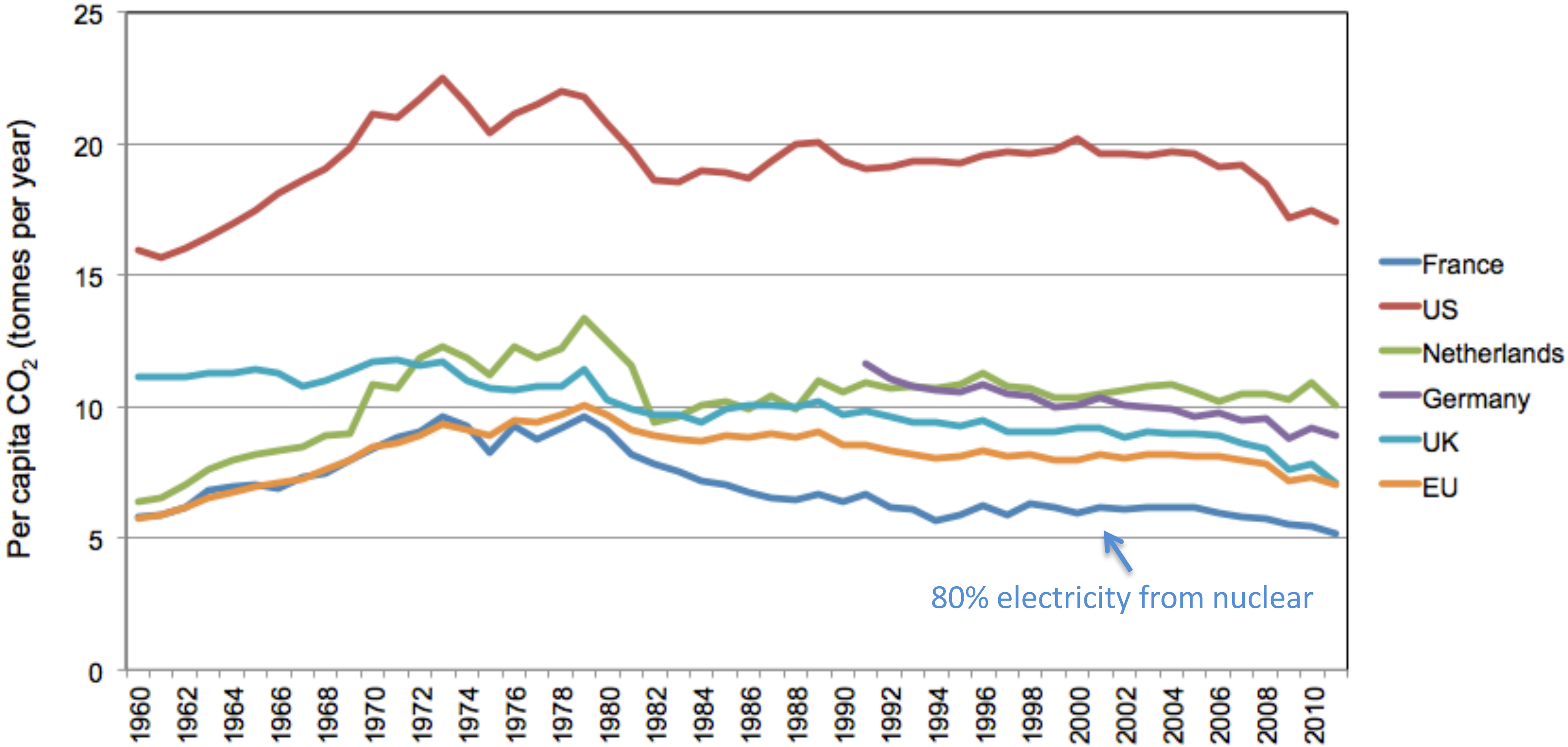
Nuclear energy – Environmental, political and security Issues

- Contribution of nuclear energy to reducing CO_2 emissions
- Public perception of nuclear energy
- Nuclear energy and proliferation
- Availability of resources
- Cost of nuclear energy
- Management of radioactivity

Future prospects of nuclear energy

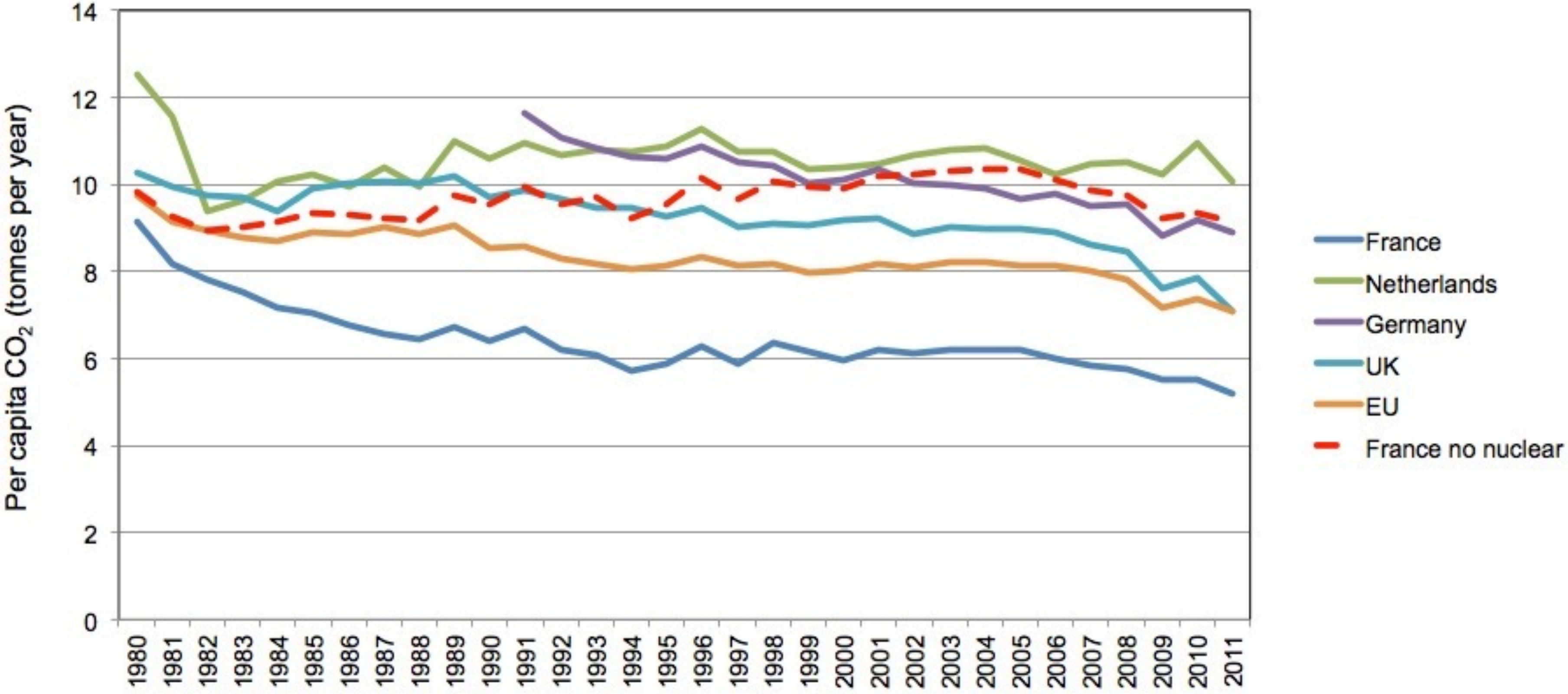
Contribution of nuclear energy to reducing CO_2 emissions



Comparison of per capita CO_2 emissions for France (where 80% of the electricity is nuclear-generated) and other industrialised countries

Data Source: World Bank ,2015

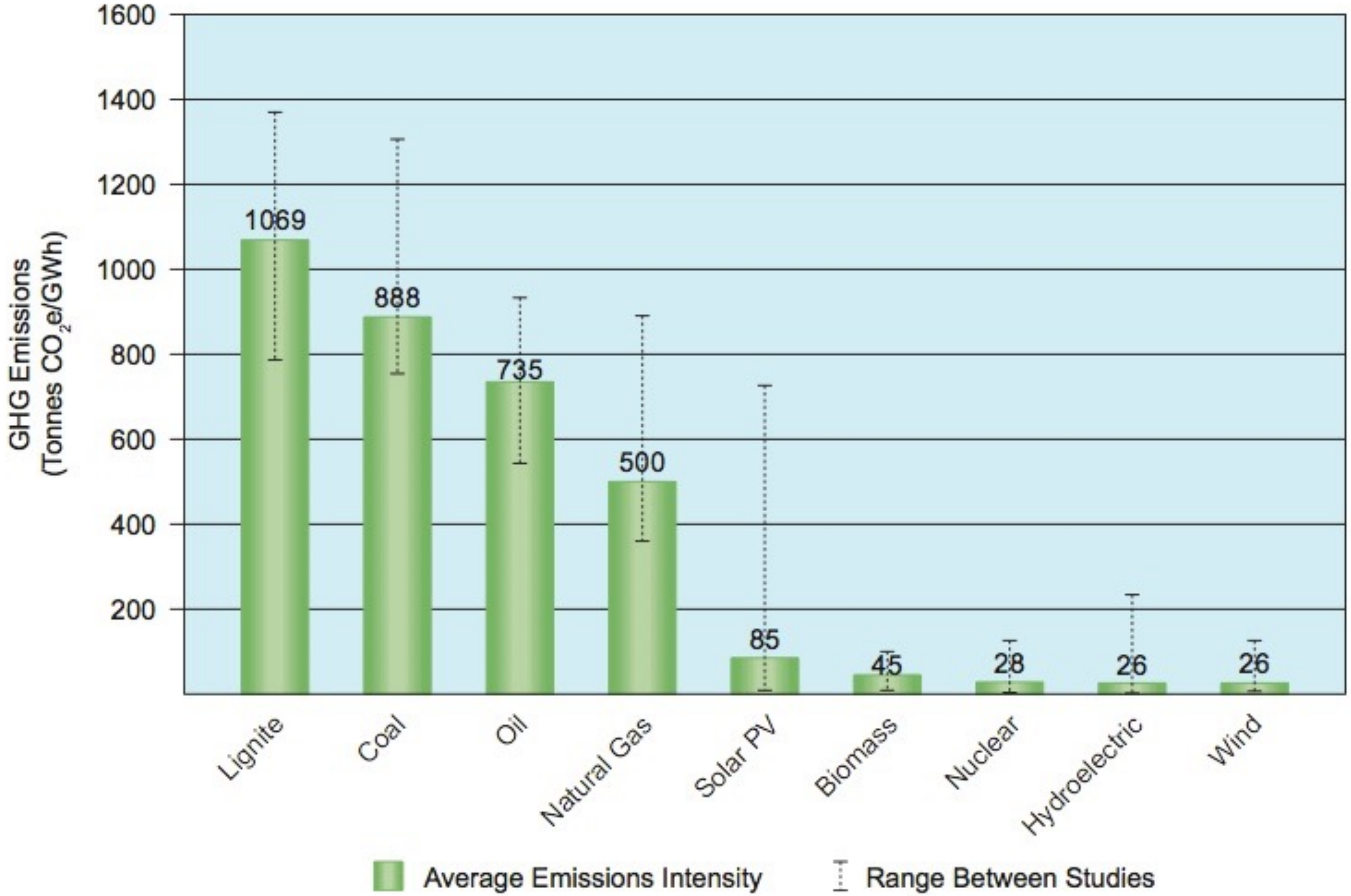
Contribution of nuclear energy to reducing CO_2 emissions



Effect of replacing the French nuclear-generated electricity with fossil-generated electricity on per capita CO_2 emissions

Data Source: World Bank ,2015; EIA Int. Stats, 2015

Contribution of nuclear energy to reducing CO_2 emissions



Comparison of Life Cycle Approach Greenhouse Gas emissions between various electricity generation sources

Source: World Nuclear Association

Contribution of nuclear energy to reducing CO_2 emissions

- GHG emissions of nuclear power plants are among the lowest of any electricity generation method, and on a lifecycle basis are comparable to wind, hydro and biomass;
- Lifecycle emissions of natural gas are 15 times greater than nuclear;
- Lifecycle emissions of coal are 30 times greater than nuclear;
- Good agreement between this and other published studies on lifecycle GHG intensities – e.g. NREL, US
- Data shows sensitivity to assumptions made (e.g., assuming gaseous difussion or centrifugation enrichment has bearing on life cycle results for nuclear).

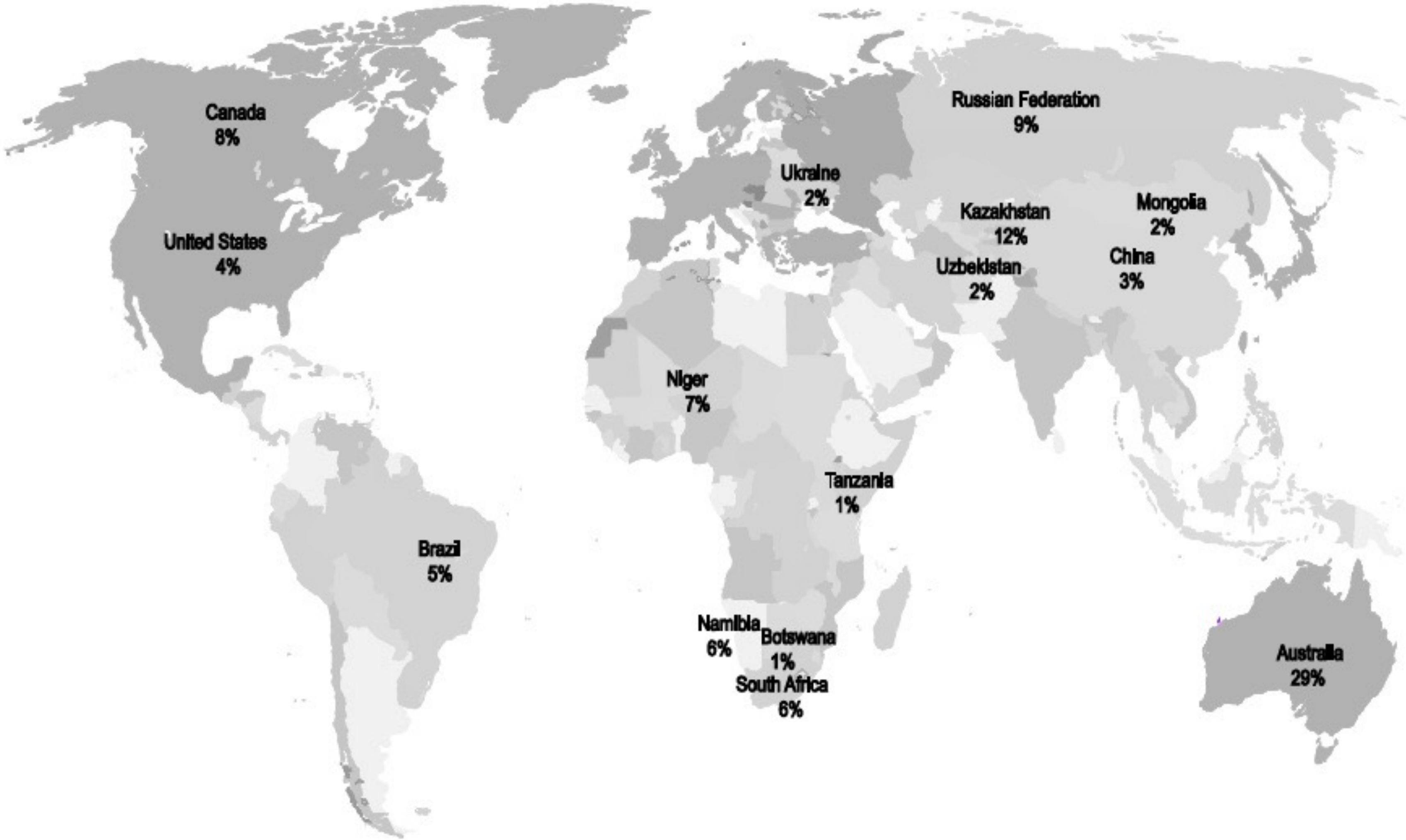
Availability of resources for nuclear energy generation

- dependent on reaction used and maximum allowable cost of the resource that is economically feasible. For U:

Resource category	2011	2013	Change (1 000 tU)[a]	% change
Identified (total)				
<USD 260/kgU	7 096.6	7 635.2	538.6	7.6
<USD 130/kgU	5 327.2	5 902.9	575.7	10.8
<USD 80/kgU	3 078.5	1 956.7	1 121.8	-36.4
<USD 40/kgU[b]	680.9	682.9	2.0	0.3
RAR				
<USD 260/kgU	4 378.7	4 587.2	208.5	4.8
<USD 130/kgU	3 455.5	3 698.9	243.4	7.0
<USD 80/kgU	2 014.8	1 211.6	803.2	-39.9
<USD 40/kgU[b]	493.9	507.4	13.5	2.7
Inferred resources				
<USD 260/kgU	2 717.9	3 048.0	330.1	12.1
<USD 130/kgU	1 871.7	2 204.0	332.3	17.8
<USD 80/kgU	1 063.7	745.1	318.6	-30.0
<USD 40/kgU[b]	187.0	175.5	11.5	-6.1

Identified uranium resources, in 1000 tU (RAR + inferred) in 2011 / 2013
(from: OECD NEA & IAEA, 2014)

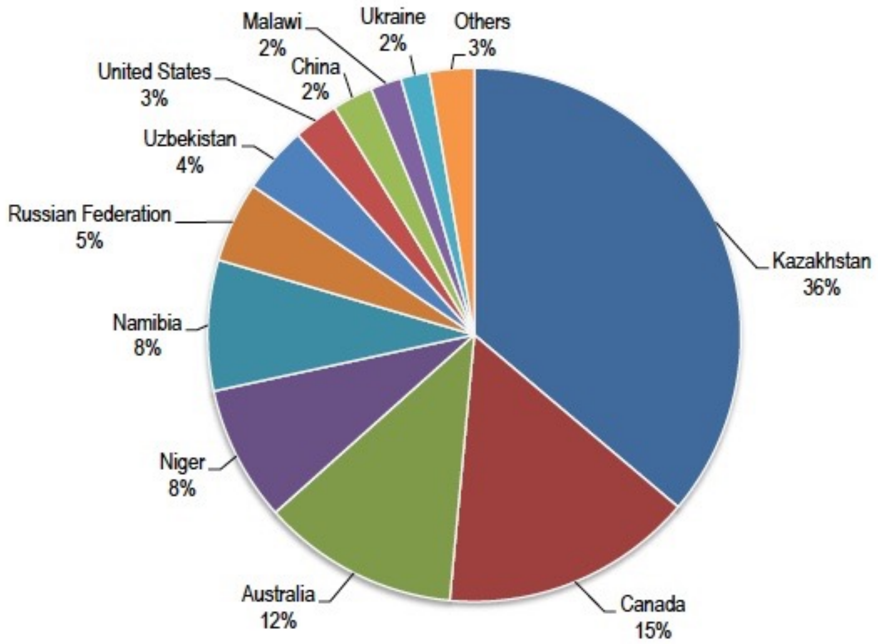
Availability of resources for nuclear energy generation



Global distribution of identified sources (<$130/kgU)
(from: OECD NEA & IAEA, 2014)

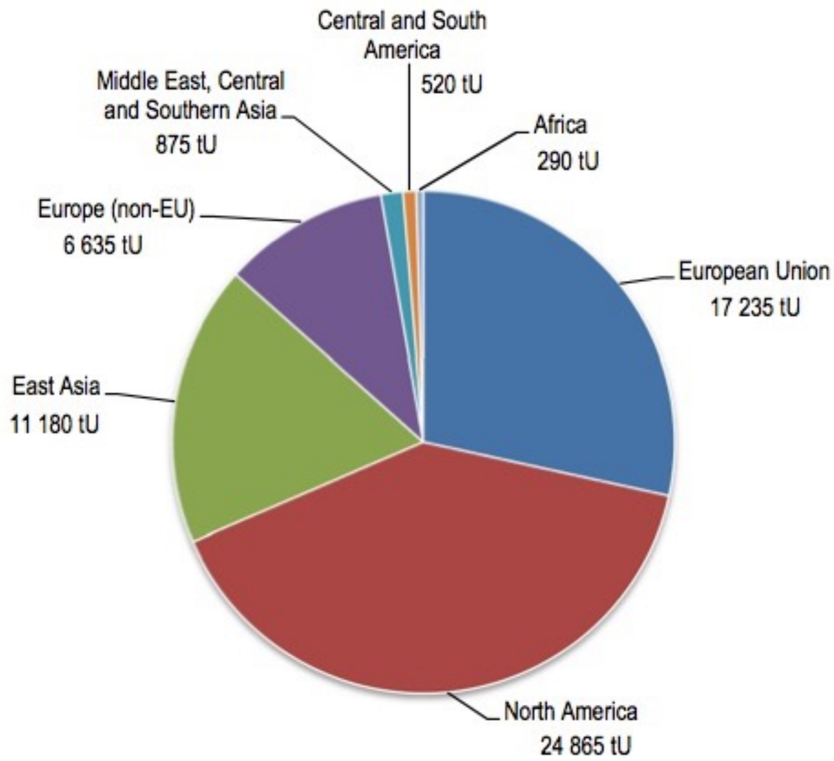
Availability of resources for nuclear energy generation

Total production = 58,816 tU



2012 World Uranium Production
(from: OECD NEA & IAEA, 2014)

Total requirement = 61,600 tU



2012 World Uranium Requirements
(from: OECD NEA & IAEA, 2014)

Availability of resources for nuclear energy generation

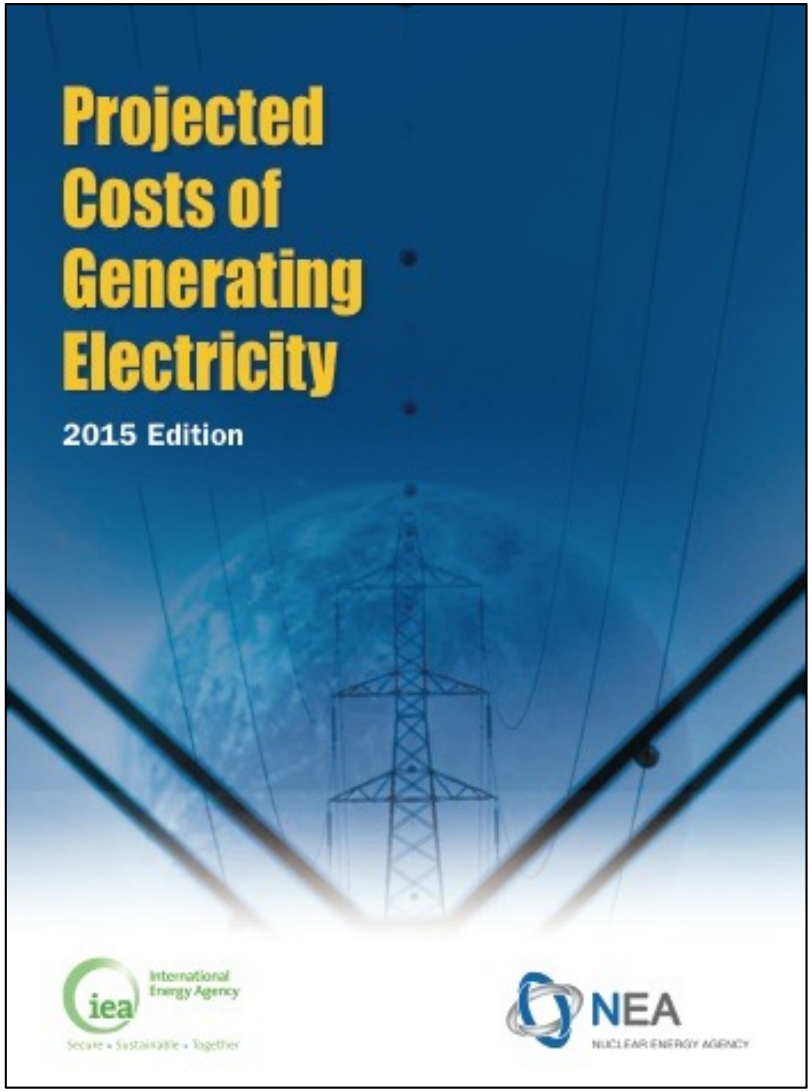
- At the current rate of consumption, identified resources at <$130/kgU are enough to last for ~100 y;

- In a robust growth scenario, lifetime of uranium supply would be shorter, but exploitation of more expensive deposits and new discoveries would probably compensate;

- The above omits unconventional resources (U as minor by-product) such as phosphate/phosporite deposits (up to 22 MtU), black shales (5.2 MtU), lignite (0.7 MtU) and even seawater (4000 MtU), which could extend lifetime for centuries;

- Also assumes current reliance on ^{235}U for energy production. Use of ^{238}U in breeder reactors and the use of Thorium fuel cycle could increase lifetime of resource to several millennia.

Cost of nuclear energy – comparison with other energy sources

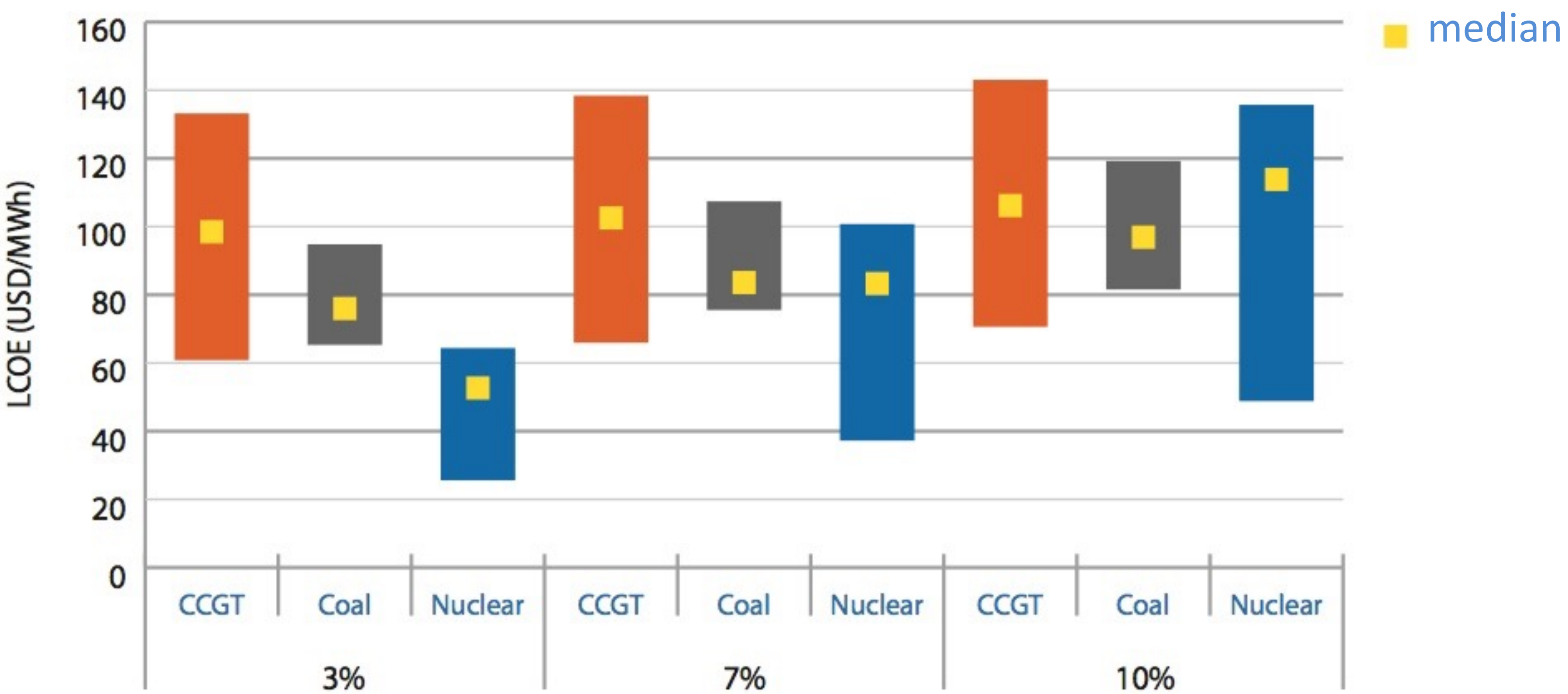


- IEA – NEA study
- Levelised costs of electricity (LCOE)
- Based on analysis of 181 plants in 22 countries

Key findings:

- significant decline in recent years in the cost of renewables
- nuclear energy costs remain in line with the cost of other baseload technologies

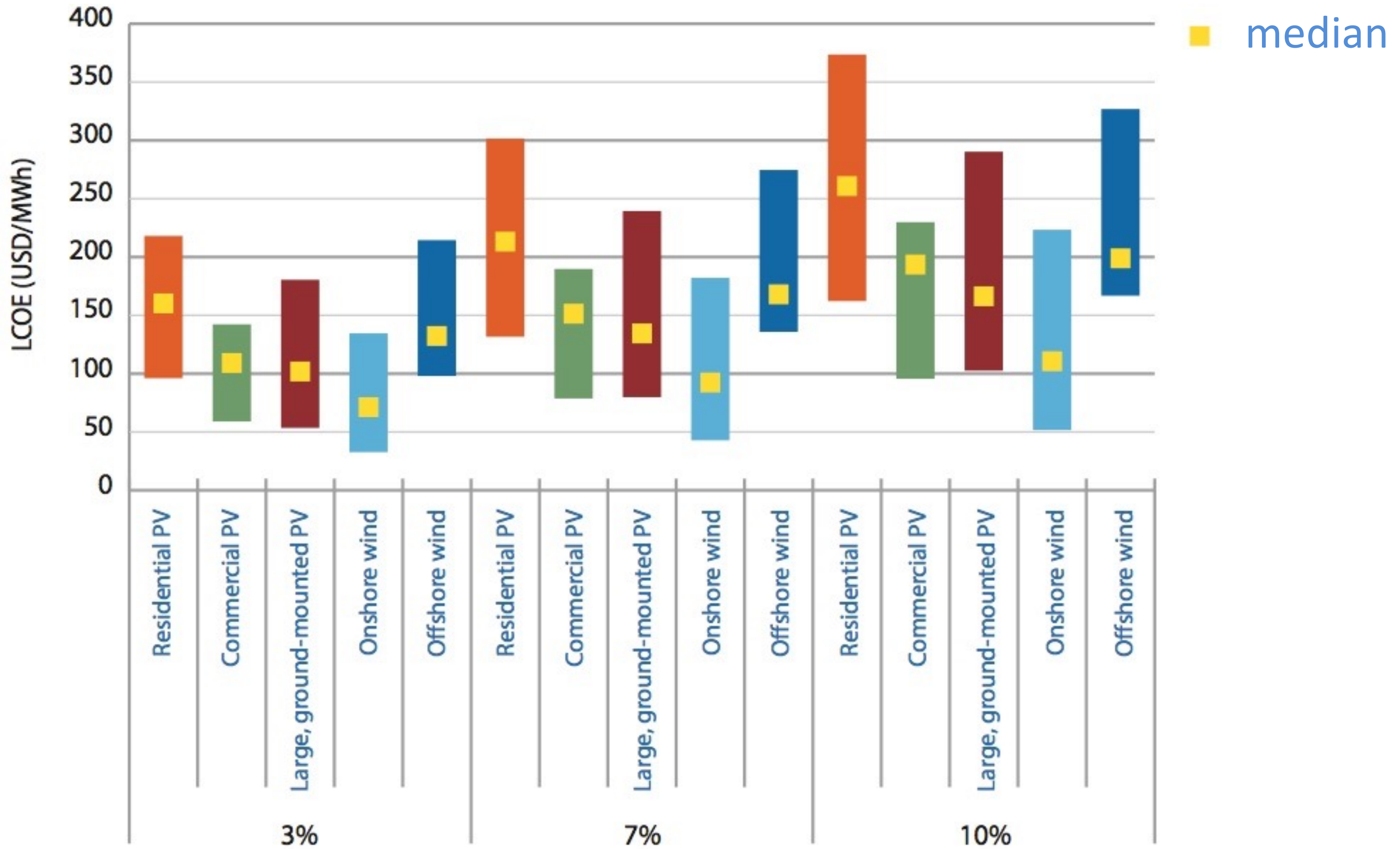
Cost of nuclear energy – comparison with other energy sources



LCOE ranges for baseload technologies (at each discount rate)

(source: IEA/NEA Projected Costs of Generating Electricity, 2015)

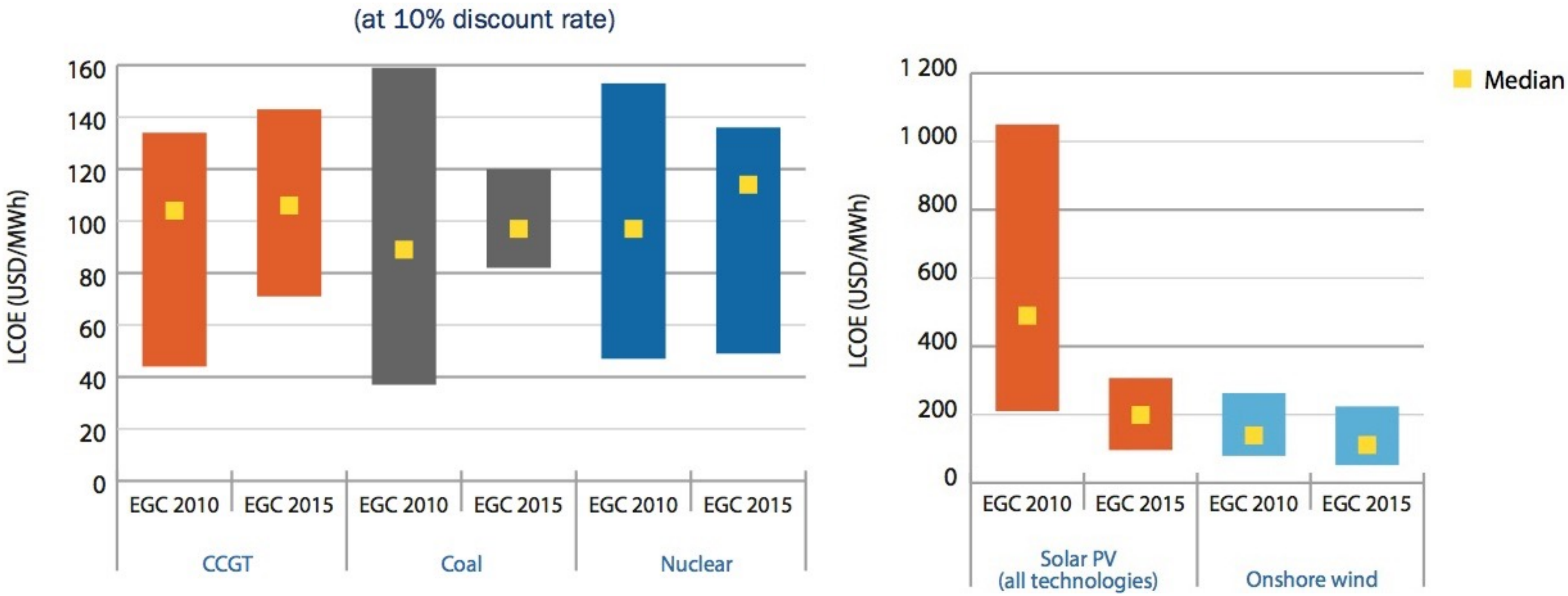
Cost of nuclear energy – comparison with other energy sources



LCOE ranges for solar and wind technologies (at each discount rate)

(source: IEA/NEA Projected Costs of Generating Electricity, 2015)

Cost of nuclear energy – comparison with other energy sources



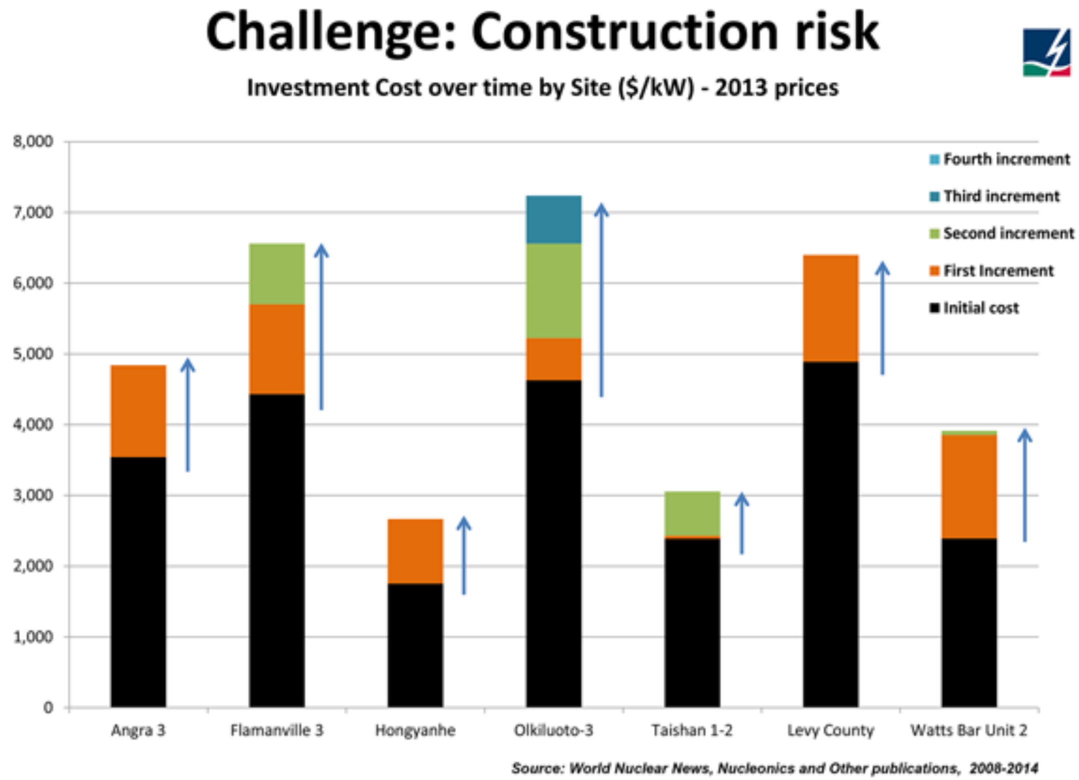
Electricity Generating Costs 2010 vs 2015 – LCOE ranges for baseload and renewable sources (at 10% discount rate)

(source: IEA/NEA Projected Costs of Generating Electricity, 2015)

Cost of nuclear energy – comparison with other energy sources

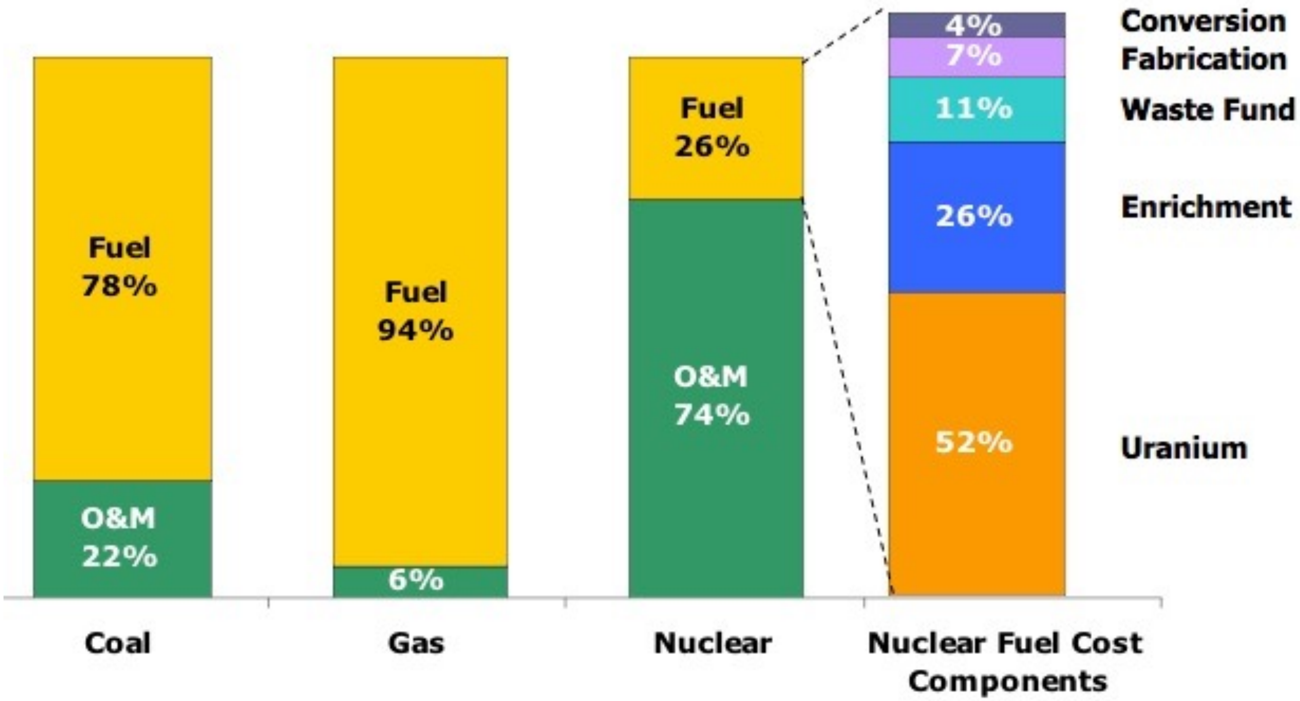
- In general, construction costs of NPPs are significantly higher than coal or gas – these contribute much of the nuclear generation costs, but once the plant is built the costs variables are minor.

- Construction and financing costs very sensitive to delays.



Cost of nuclear energy – comparison with other energy sources

- Fuel costs are much less than those associated with gas or coal, even when processing steps (enrichment, fabrication) and management and disposal of waste are included.
- Relatively insensitive to uranium ore prices.



Fuel as a percentage of electric power operating costs for coal, gas and nuclear (2005 data)

(source: Global Energy Decisions, 2006)

Management of radioactive waste in nuclear power generation

- Radioactive by-products generated in the front end (low radioactivity) and the back end (high radioactivity) of the nuclear fuel cycle
- Long-term exposure to radiation during mining can lead to health effects – e.g. U miners and radon exposure.
- Milling process results in uranium mill tailings containing other radioactive compounds that must be handled carefully.

Management of radioactive waste in nuclear power generation

- During routine operation of nuclear reactors, risk to workers is managed by the use of protective equipment, shielding and the monitoring of doses – which must be kept below maximum allowable exposure (as set by legislation).
- Radiation risk to public is very small, and requires major failure of the reactor core and the containment systems.
  - Three Mile Island: despite core meltdown, containment prevented any significant releases to atmosphere;
  - Chernobyl: environmental and health consequences due to lack of containment and poor reactor design;
  - Fukushima: no acute health effects (containment and evacuation), but important disruption to energy supply and huge economic consequences.

Management of radioactive waste in nuclear power generation

- These accidents have contributed to public's perception of nuclear as an unsafe source of energy.

- Comparison of health effects for different forms of power generation in a number of studies shows the health burdens to be greatest for fossil fuels (especially coal, lignite and oil) .

- Nuclear power has one of the lowest air pollution-related effects, and one of the smallest levels of direct health effects (either occupational or public).

- A 2005 European Union study called ExternE (Externalities of Energy) found that nuclear has a lower health burden than some of the renewables (e.g. biomass and solar PV), and is similar to that of wind or hydropower.

Management of radioactive waste in nuclear power generation

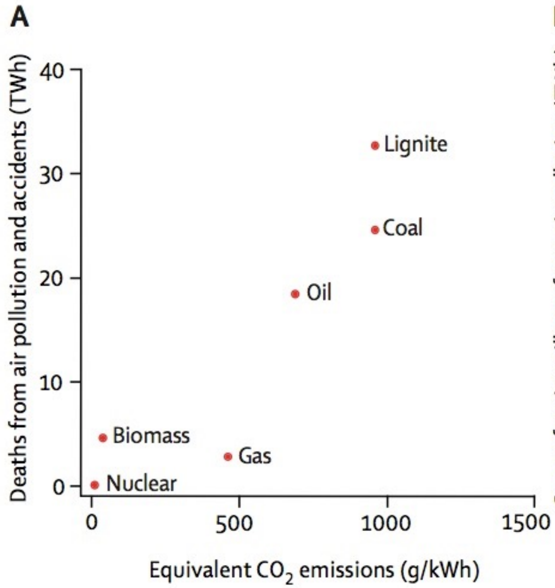
ExternE results – Health effects of electricity generation in Europe (deaths / TWh)

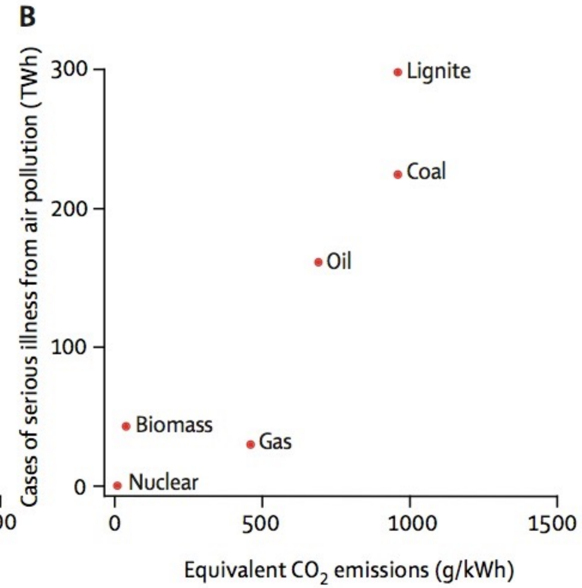
	Deaths from accidents		Air pollution-related effects		
	Among the public	Occupational	Deaths*	Serious illness†	Minor illness‡
Lignite[30]	0·02 (0·005–0·08)	0·10 (0·025–0·4)	32·6 (8·2–130)	298 (74·6–1193)	17 676 (4419–70 704)
Coal[31]	0·02 (0·005–0·08)	0·10 (0·025–0·4)	24·5 (6·1–98·0)	225 (56·2–899)	13 288 (3322–53 150)
Gas[31]	0·02 (0·005–0·08)	0·001 (0·0003–0·004)	2·8 (0·70–11·2)	30 (7·48–120)	703 (176–2813)
Oil[31]	0·03 (0·008–0·12)	..	18·4 (4·6–73·6)	161 (40·4–645·6)	9551 (2388–38 204)
Biomass[31]	..	..	4·63 (1·16–18·5)	43 (10·8–172·6)	2276 (569–9104)
Nuclear[31,32]	0·003	0·019	0·052	0·22	..

Data are mean estimate (95% CI). *Includes acute and chronic effects. Chronic effect deaths are between 88% and 99% of total. For nuclear power, they include all cancer-related deaths. †Includes respiratory and cerebrovascular hospital admissions, congestive heart failure, and chronic bronchitis. For nuclear power, they include all non-fatal cancers and hereditary effects. ‡Includes restricted activity days, bronchodilator use cases, cough, and lower-respiratory symptom days in patients with asthma, and chronic cough episodes. TWh=10^{12} Watt hours.

Table 2: **Health effects of electricity generation in Europe by primary energy source (deaths/cases per TWh)**

(source: Markandya & Wilkinson, 2007)



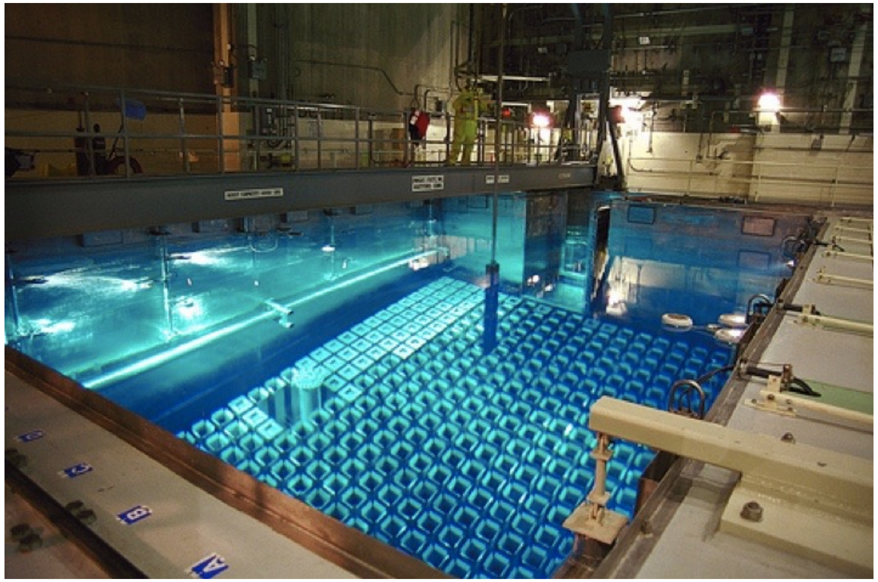


	Cases	Percentage due to coal
Accident-related deaths		
Among the public	6	44%
Occupational	13	99%
Air pollution		
Deaths	3778	85%
Serious illness	35 186	84%
Minor illness	1 853 152	94%

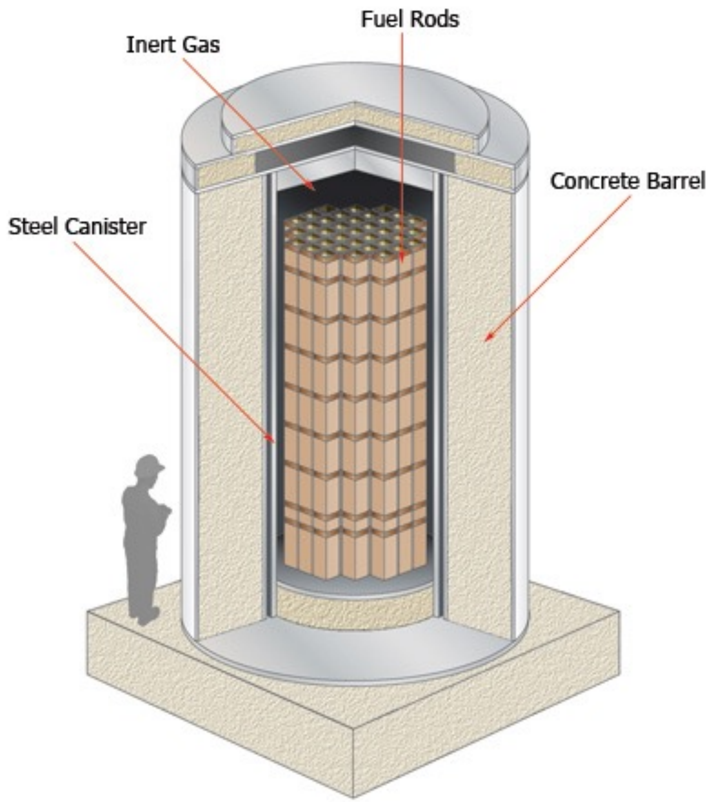
Table 3: **Health burdens from electricity generation in the UK, 2001**

Management of High Level Waste (HLW)

- HLW primarily made up of spent nuclear fuel.
- After a few months in the reactor’s cooling pool, the spent fuel can moved into longer-term (wet or dry) storage facilities on site, or in some off-site location.



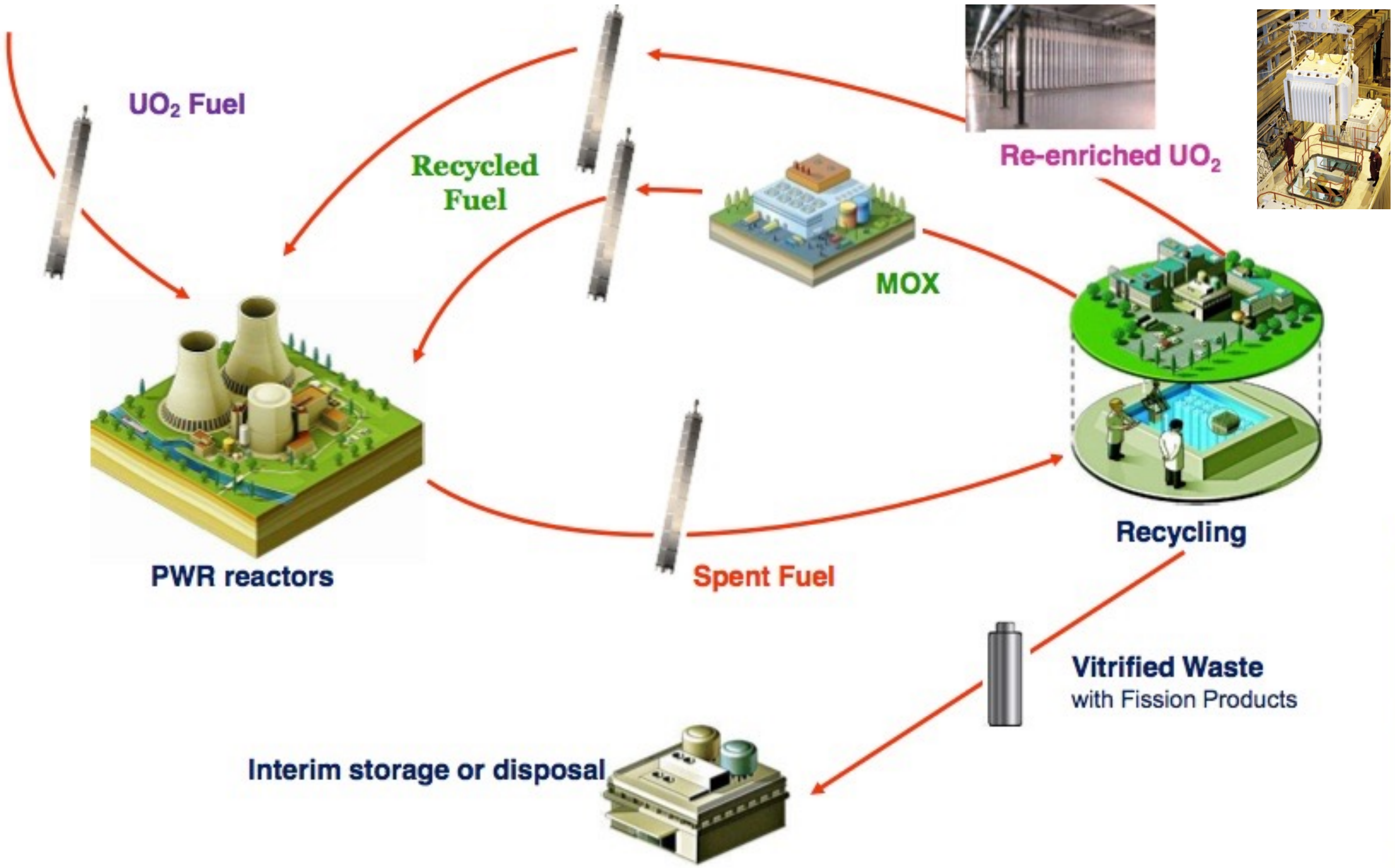
Spent fuel water pond

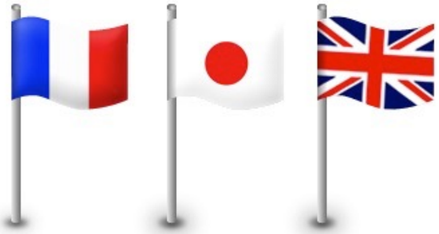


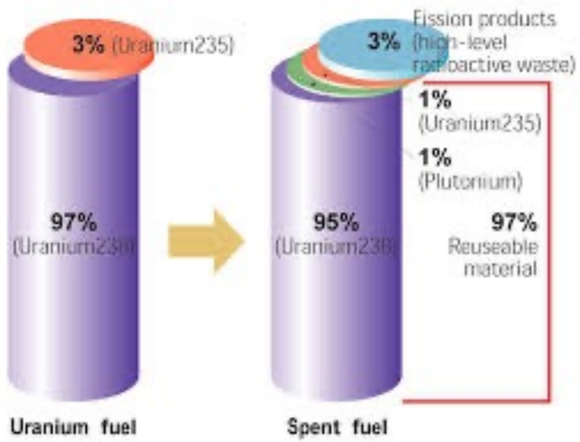
Spent fuel storage cask

Management of High Level Waste (HLW)

An alternative to long-term storage is reprocessing, in which useful components (U, Pu) are separated and recycled.

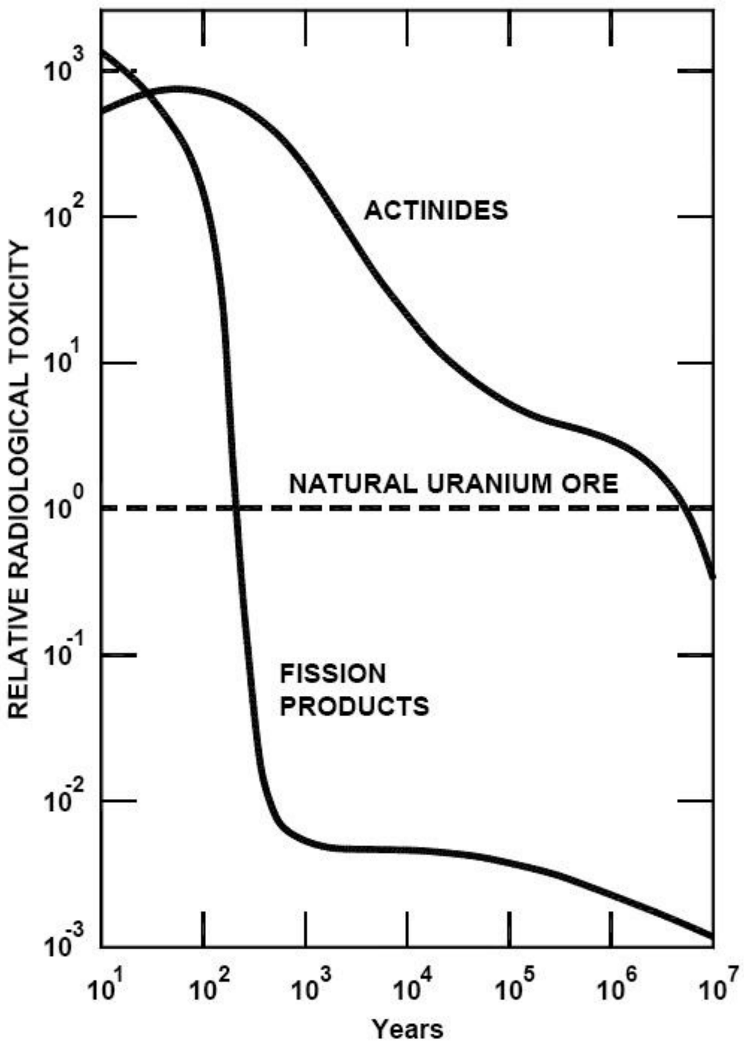






Reprocessing and recycling of spent nuclear fuel

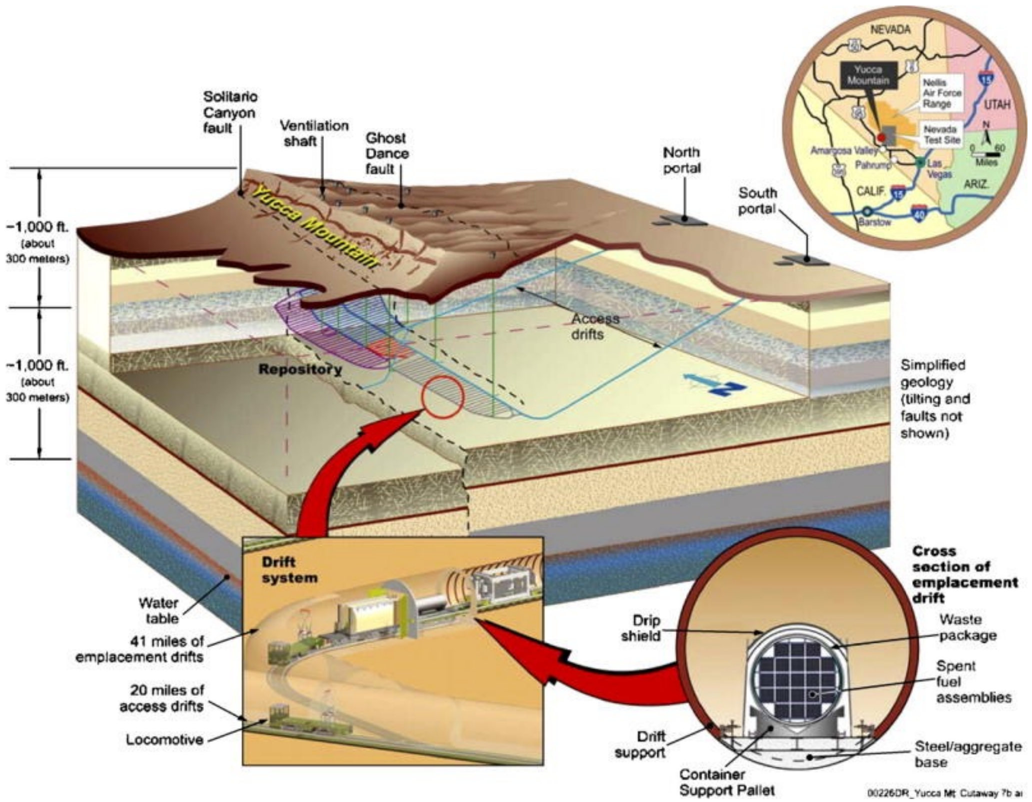
Management of High Level Waste (HLW)



Radiological toxicity of LWR spent fuel constituents
as a function of time

Management of High Level Waste (HLW)

One of the options for permanent storage of HLW (once-through or reprocessed waste) is burial deep underground in stable rock formation to minimise seismic activity or seepage of water into the waste.



Yucca Mountain radioactive waste underground facility

The future of nuclear energy

- In the short term, nuclear energy will continue to produce thousands of TWh per year, saving emission of gigatons of CO_2-equivalent GHGs from fossil fuel burning;
- While some countries may phase out nuclear energy (e.g., Germany, Belgium, Sweden), others (e.g., China, India, France) will grow their nuclear power capacity.

The future of nuclear energy

- Enough fuel resources to sustain current use for many decades;
- Possible to extend this to centuries or millennia by exploitation of unconventional sources or the development of breeder reactors;
- Capital costs are high, and future designs will have to reduce this in order to be cost competitive with other alternatives;
- Long-term use of nuclear power will largely depend on its acceptance by the public by demonstrated improvements in safety and reliability of reactors, robust control of fissile materials to prevent proliferation, and a satisfactory resolution of the storage of HLW.