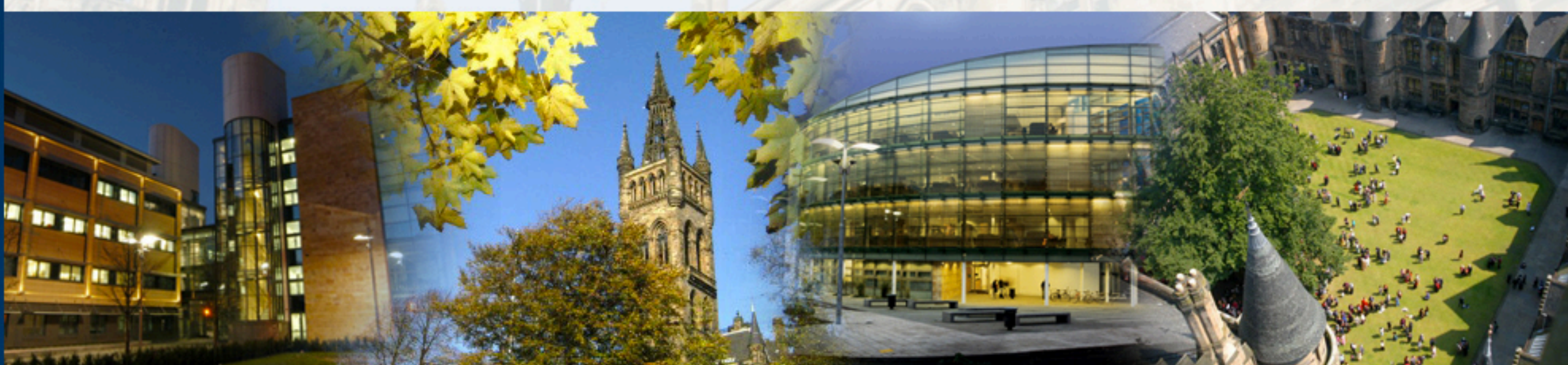
Nuclear Energy

Frontiers of Physics Lecture 1 (F3)
Dan Protopopescu



Structure of the course

- Nuclear power today
  - how it works
  - why do we need it
  - what countries use it
- Public perception
  - radiation, radioactive contamination
  - nuclear waste
  - nuclear bombs and reactors
  - accidents
- Technology explained
  - types of nuclear reactors
  - safety features
- Future
  - advanced nuclear power reactors
  - nuclear fusion

What is nuclear energy ?

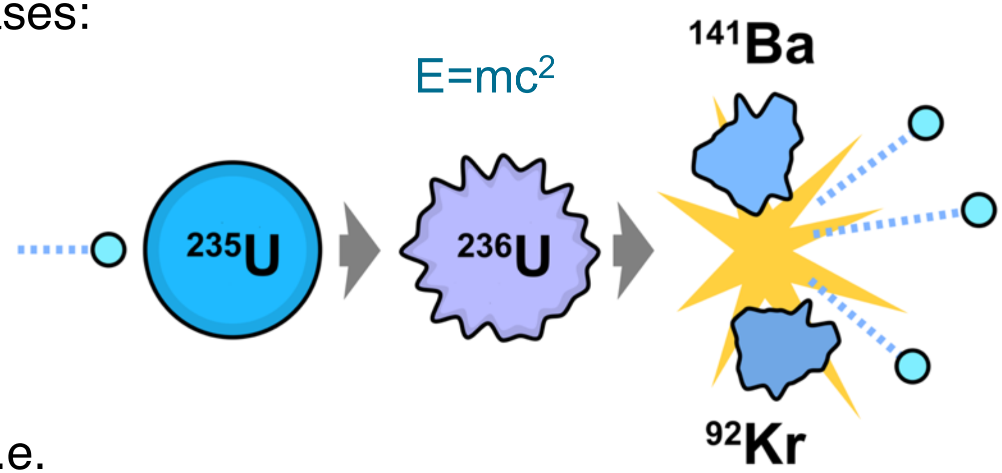
Nuclear energy originates from the splitting of atomic nuclei in a process called **fission**.

At a power plant, the energy produced from *controlled* fission generates heat to produce steam, which is then used in a turbine to generate electricity.

Each fissioning ^{235}U nucleus releases:

- prompt gamma radiation
- beta radiation from fission fragments
- approximately 200 MeV of energy

This energy ends up as thermal, i.e. ultimately ***heat***



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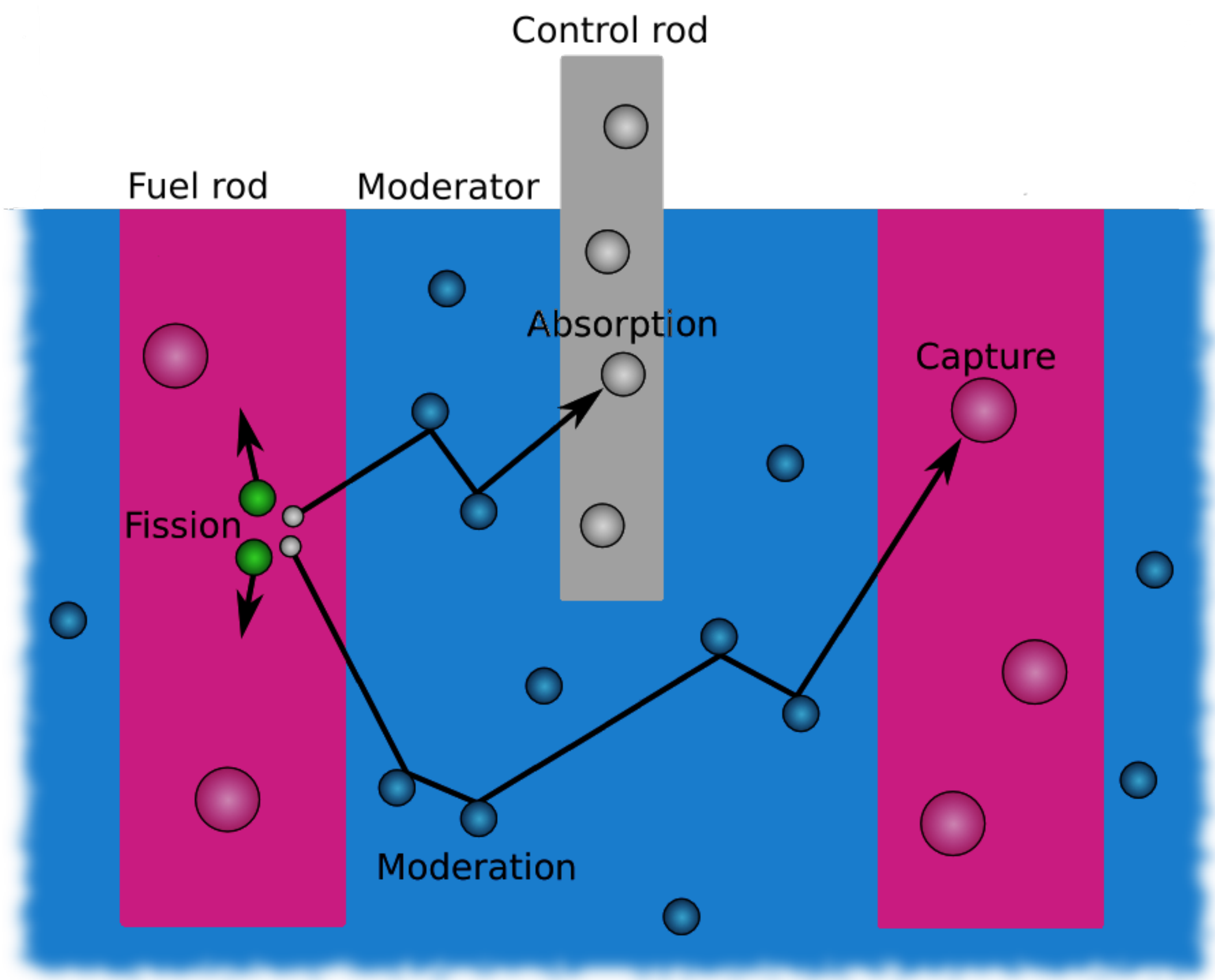
Thermal Nuclear Reactor

- A ^{235}U nucleus captures a neutron and fissions
- 2-3 fast neutrons are released
- the neutrons are slowed down in the moderator
- any of these neutrons can be absorbed by another ^{235}U nucleus which will fission ...

... and so forth



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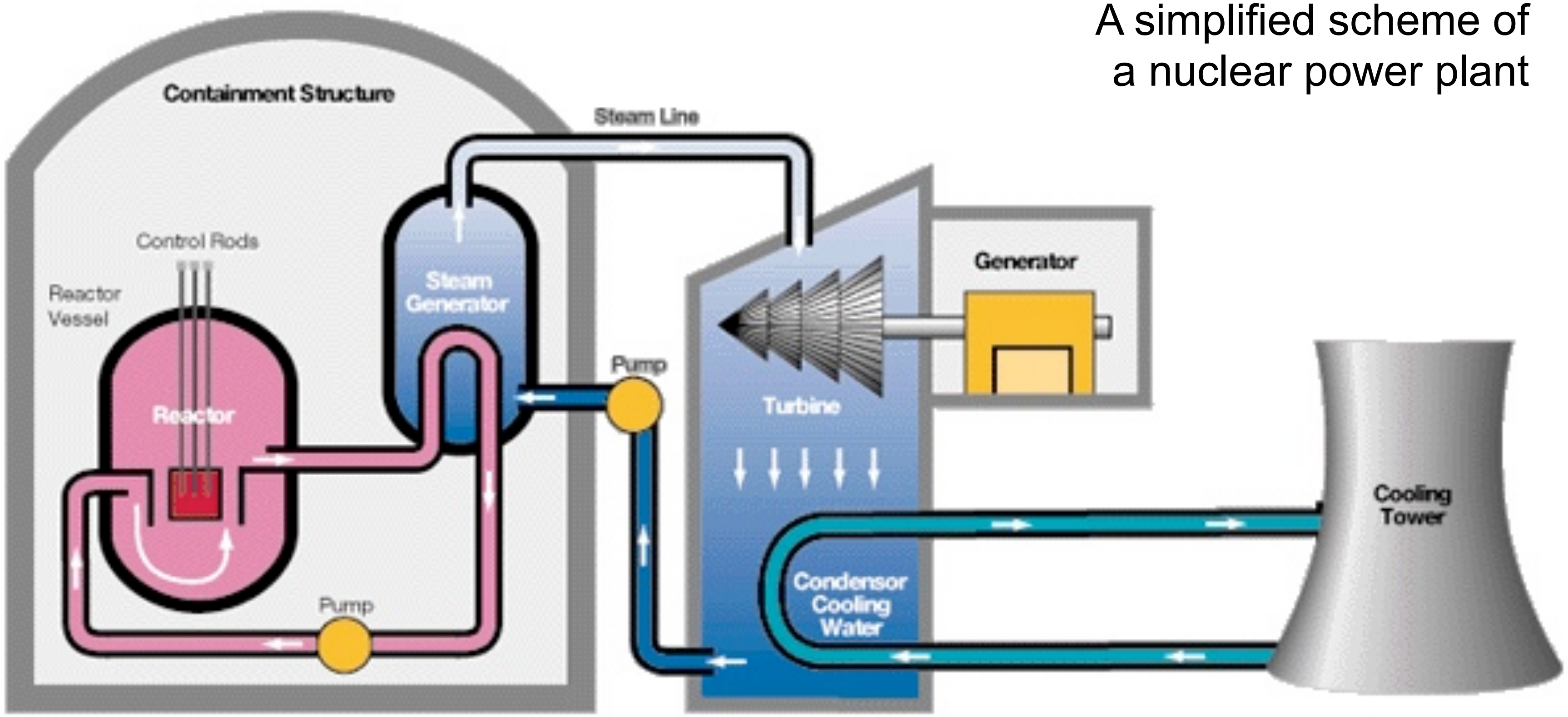
How does it work ?

A simplified scheme of
a nuclear power plant



Why do we need nuclear energy ?

- We need more and more energy: in the next 50 years, it is estimated that the population of the world will use *more energy than the total consumed in all previous history*
- Most of the energy generated today comes from **burning** fossil fuels to make electricity, power vehicles or heat buildings
- When *fossil fuels* are burned, waste products are dispersed directly into the atmosphere
- This waste takes the form of carbon dioxide CO_2 and particulates, which contribute to the greenhouse effect
- Some numbers:
  - 30.000.000.000 tonnes of CO_2 each year, or
  - 80.000.000 tonnes each day or
  - 950 tonnes per second
  - North Americans release 54 kg CO_2 per person per day
  - Europeans release 23 kg CO_2 per person per day

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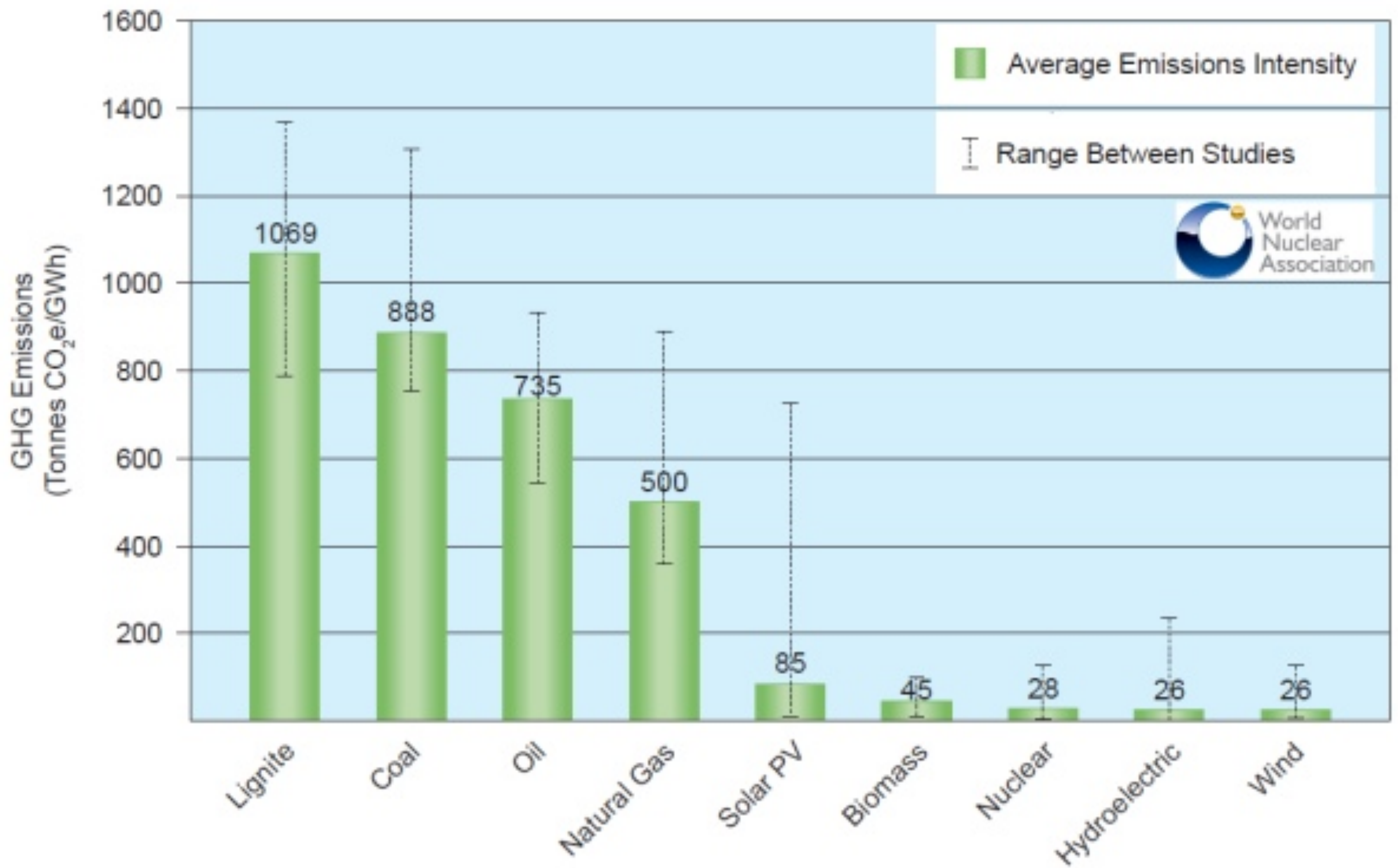
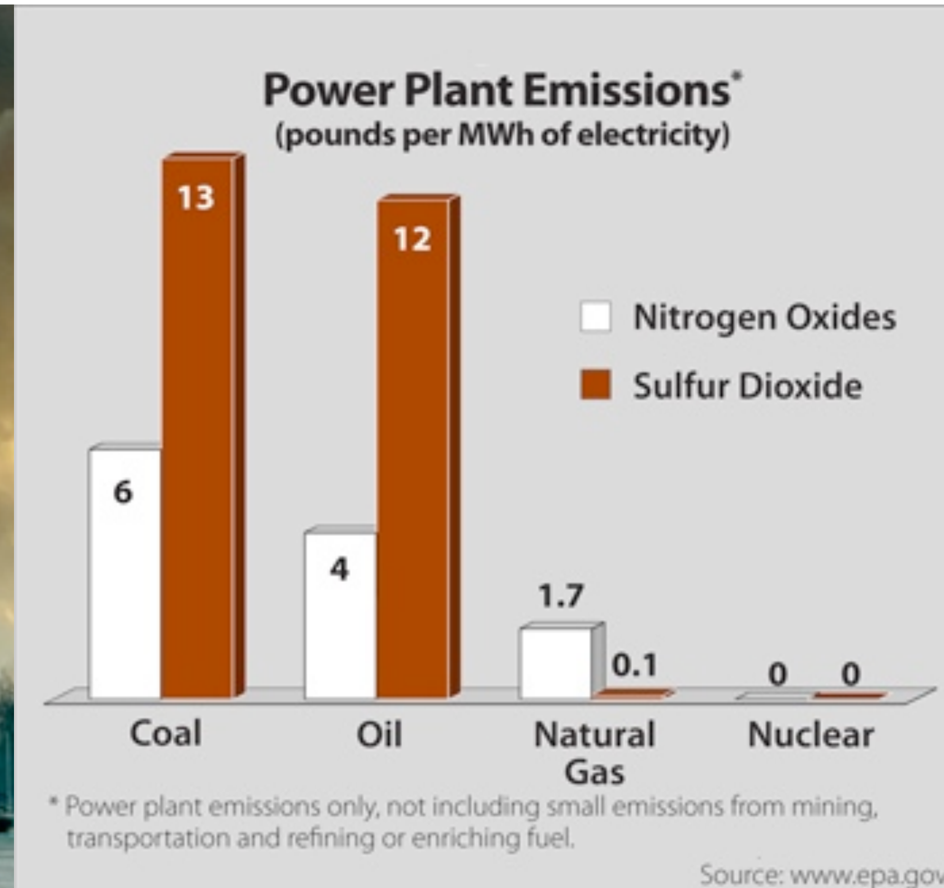
Heat content of various fuels

Fuel	Heat value	% Carbon	CO_2
Dry firewood	16 MJ/kg	42	94 g/MJ
Gasoline/Diesel fuel	44-46 MJ/kg		
Crude oil	42-44 MJ/kg	89	70-73 g/MJ
Methanol	20 MJ/kg	37	
Natural gas	38 MJ/m^3	76	52 g/MJ
Hard black coal	25 MJ/kg	67	90 g/MJ
Sub-bituminous coal	18 MJ/kg		
Lignite/brown coal	10 MJ/kg	25	116 g/MJ (1250 g/kWh)
Hydrogen	121 MJ/kg	0	0
Natural Uranium in LWR	500,000 MJ/kg	0	0
Natural Uranium in LWR with Uranium and Plutonium recycle	650,000 MJ/kg	0	0
Uranium enriched to 3.5% in LWR	3,900,000 MJ/kg	0	0
Natural Uranium in FNR	28,000,000 MJ/kg	0	0

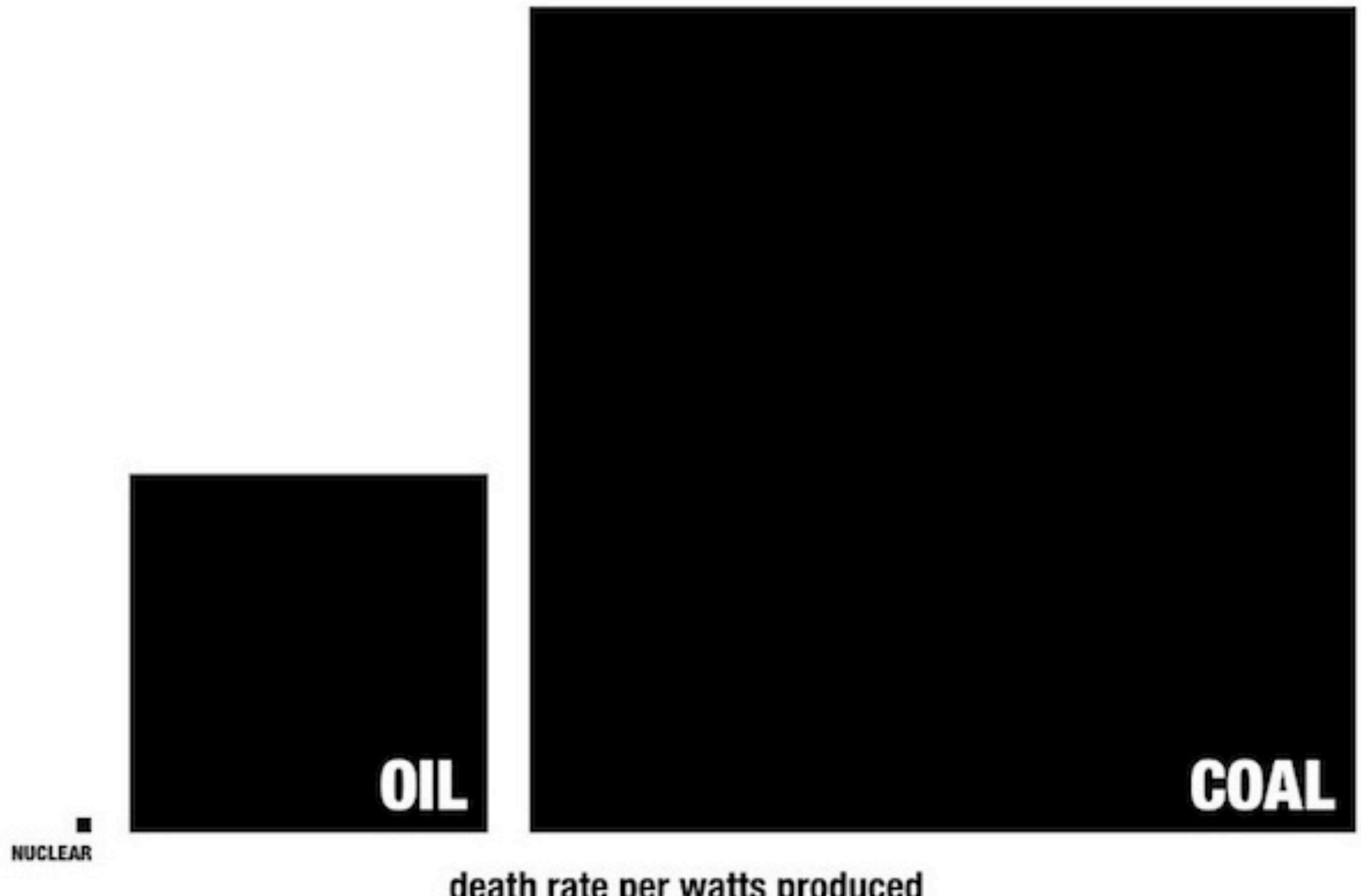
CO_2 emission comparisons



Pollution comparisons



Coal and oil vs. nuclear



How many wind turbines ?

- Sizewell B reactor: 1195 MWe
- Offshore wind turbine: 7.5 MW

1 PWR = 160 WT

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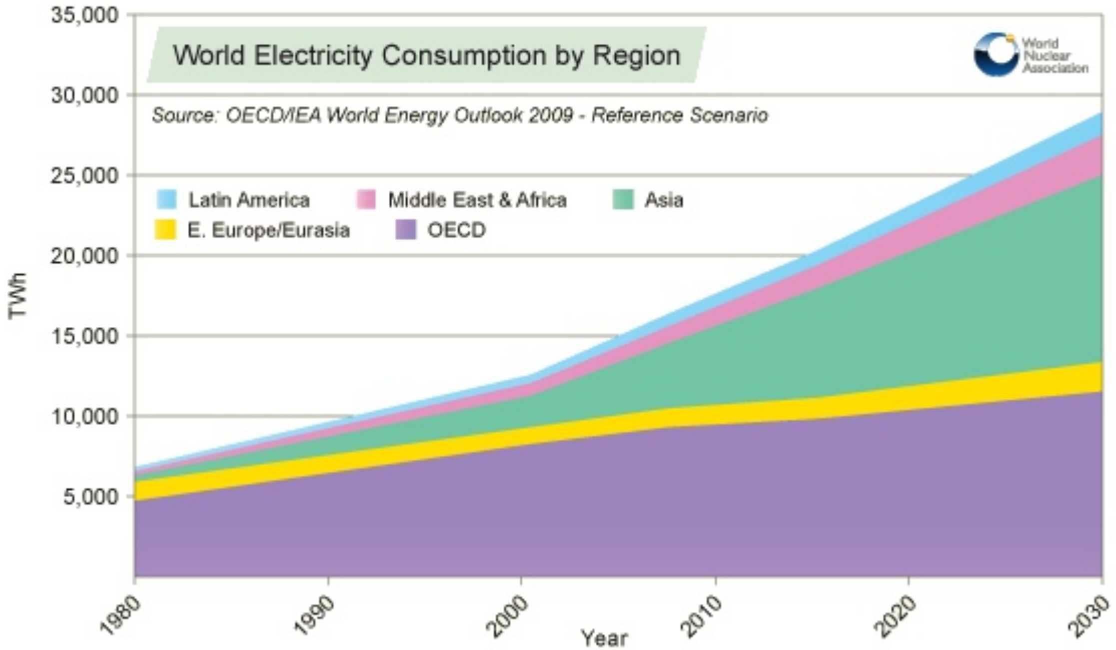
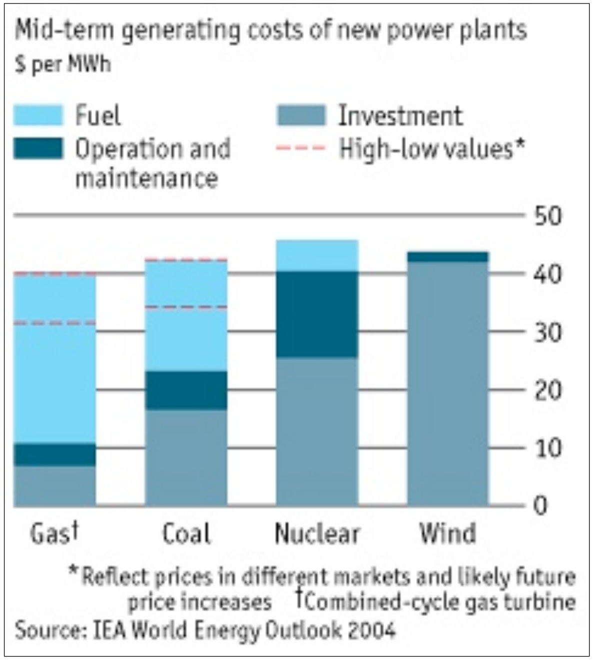
Energy demand and Costs

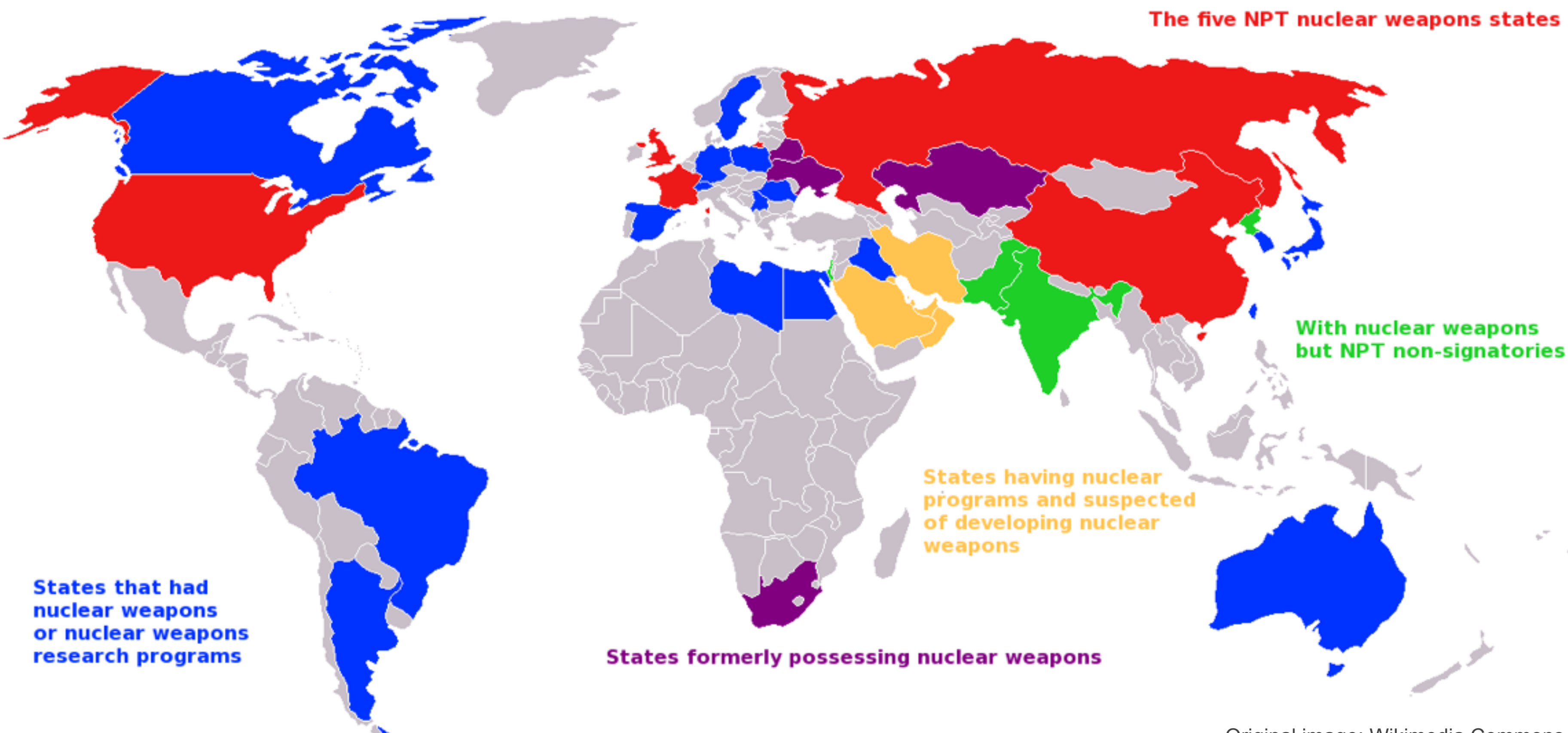
The International Energy Agency projects that renewables can provide only 6% of the world electricity needs by 2030





Nuclear energy is the only proven option with the capacity to provide scalable clean electricity on a global scale

Nuclear weapons worldwide



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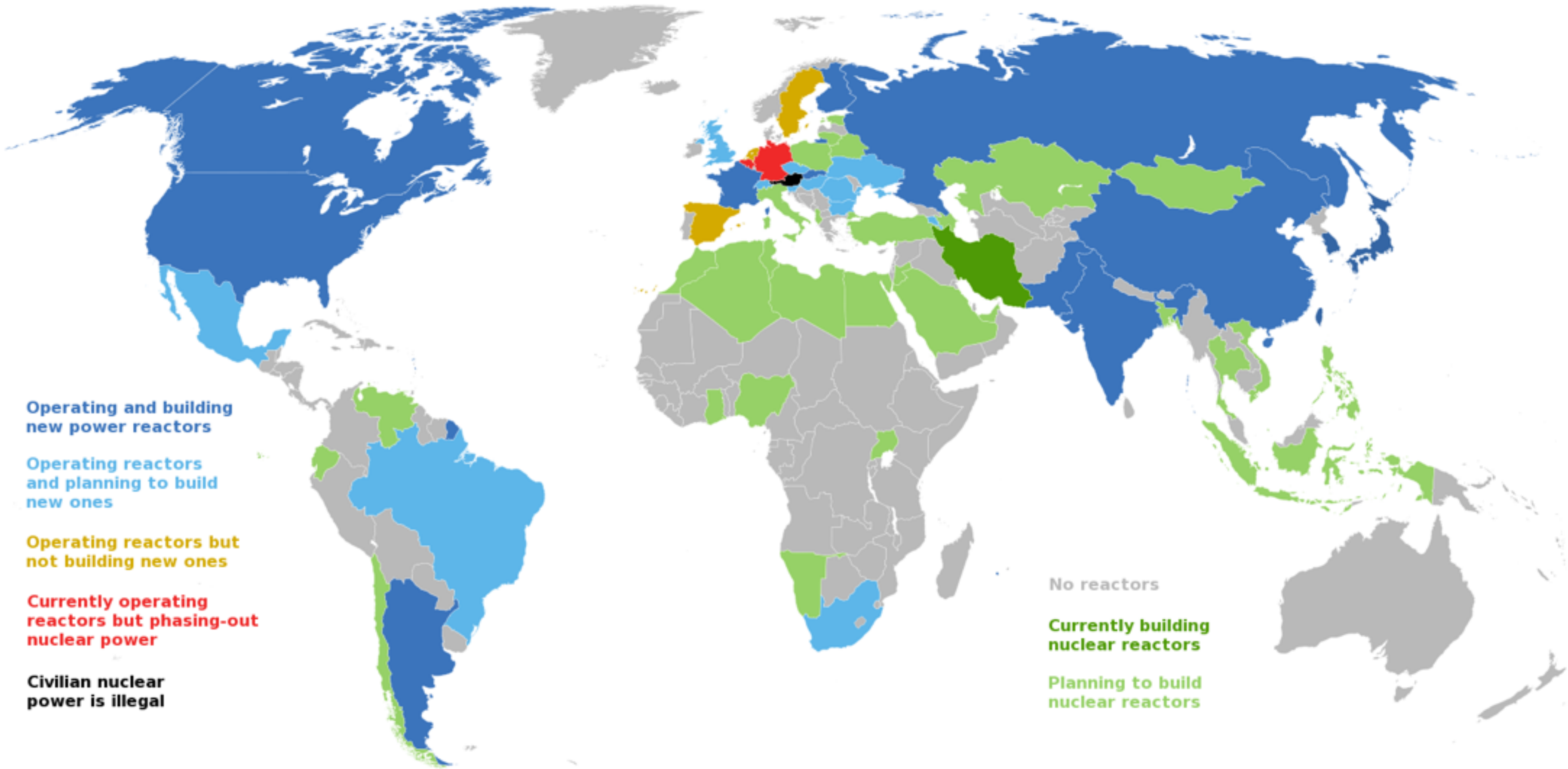
Commercial Nuclear Power



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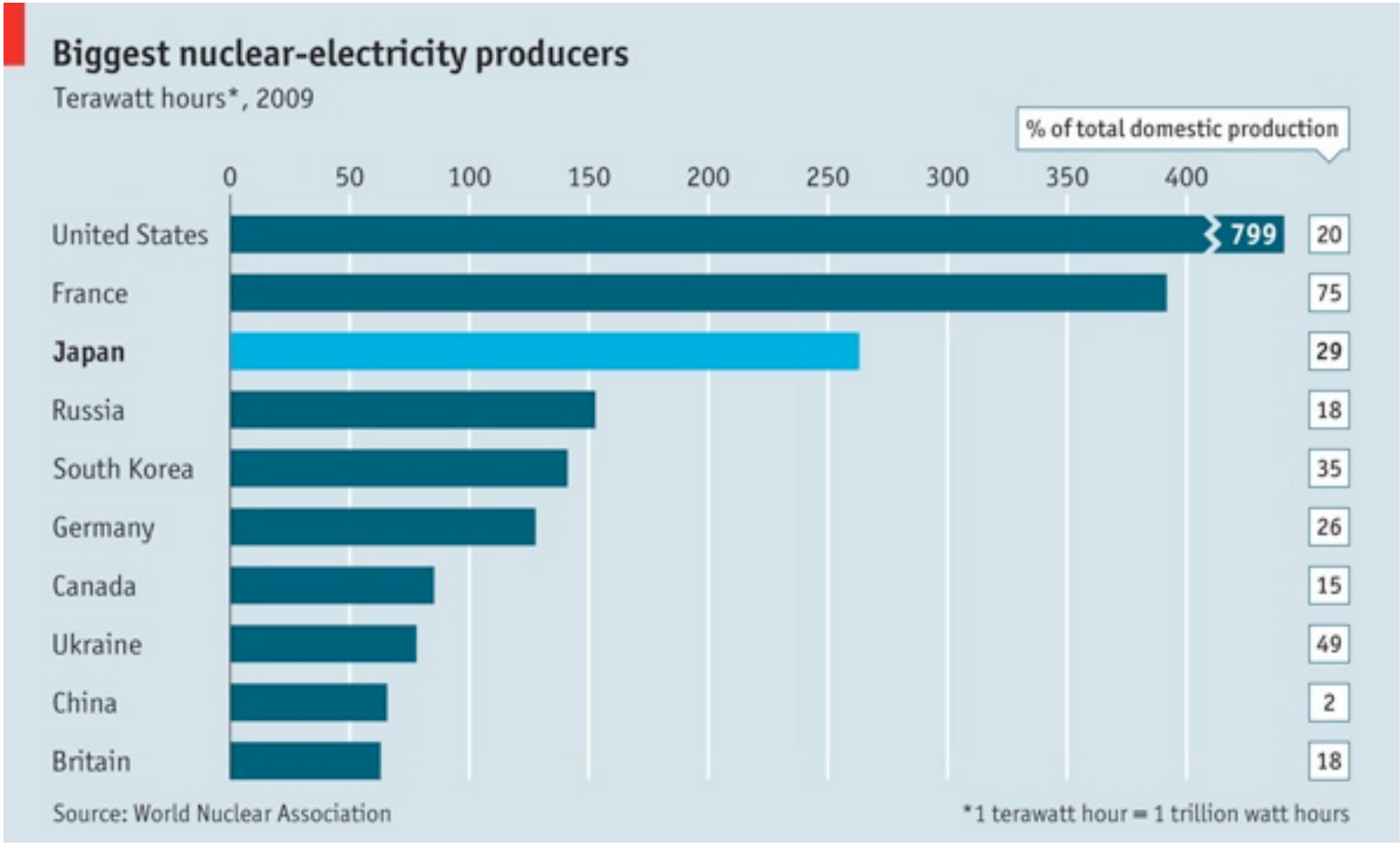
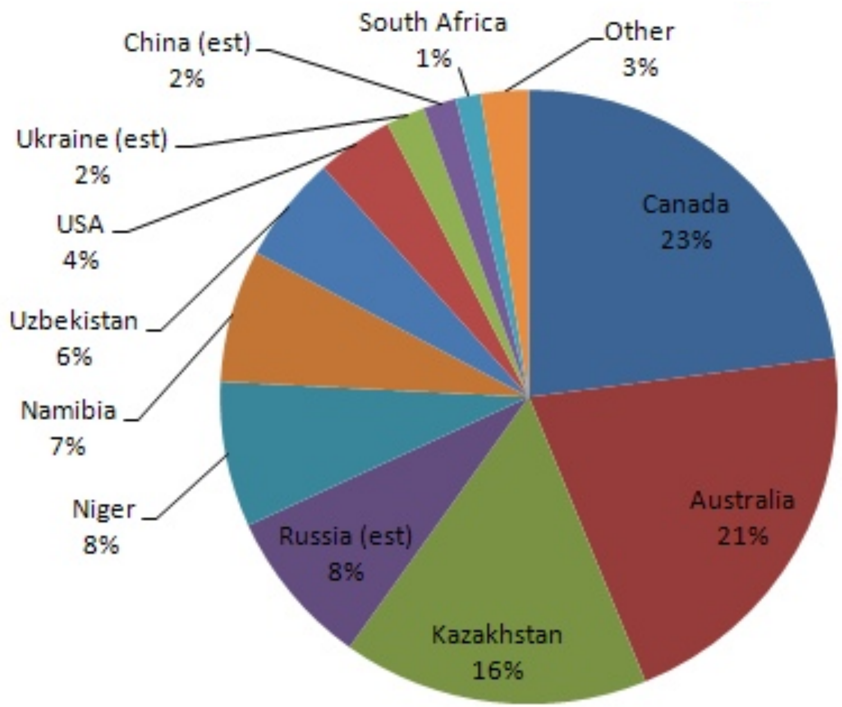
Nuclear Power



Uranium mining

- Extracted via open-pit mining
- Then *milled*: ground into a fine powder and chemically treated to leach out uranium
- What is commercialised is U_3O_8 - the so-called *yellowcake*
- This is converted to gaseous UF_6, enriched to a specific ^{235}U concentration, then converted to oxide for fuel manufacture
- Typical fuel pellets are UO_2
- Yellowcake peaked at $300/kg and then dropped to ~$60/kg
- Based on current production rates, it is estimated that reserves will last for about a century



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Uranium from seawater ?

- Low concentrations 3.3mg/m3, but practically limitless reserves
- There is technology with which it could be extracted at $240/kg

Public perception

Radiation, explosions, and nuclear waste

Radiation

- **Definitions:**
  - **Radiation** - energy traveling in the form of particles or waves, for example: microwaves, radio waves, light, medical X-rays, alpha, beta, gamma radiation
  - **Radioactivity** - a natural process through which unstable atoms of an element radiate excess energy in the form of particles or waves
  - **Radioactive material** - material that emits radiation
  - **Radioactive contamination** - radioactive material in unwanted places
- **Important facts:**
  - Radiation is commonplace
  - A person exposed to radiation does not become contaminated
  - Contamination is the result of direct contact with removable radioactive material
  - The distinction between harmful and safe depends on *quantity*. This is true about everything from paracetamol to arsenic
  - Dose is important

Banana Equivalent Dose

Bananas are a natural source of radioactive isotopes.

Eating one banana = 1 BED = 0.1 μSv = 0.01 mrem

Number of bananas	Equivalent exposure
100,000,000	Fatal dose (death within 2 weeks)
20,000,000	Typical targeted dose used in radiotherapy (one session)
70,000	Chest CT scan
20,000	Mammogram (single exposure)
1000	Chest X-ray
700	Living in a stone, brick or concrete building for one year
400	Flight from London to New York
100	Average daily background dose
50	Dental X-ray
1 - 100	Yearly dose from living near a nuclear power station
3	Same near a coal-fired power plant

2

Nuclear waste

Common concerns:

- Nuclear waste (spent fuel) is an unresolved problem
- The nuclear industry produces horrific wastes that will be an enduring nightmare for our descendants
- Nuclear reactors are unsafe, the Fukushima accident just proved it

Facts:

- The nuclear industry is the only energy-producing industry that fully manages its wastes, and bears the costs
- In all countries producing nuclear energy there are well established procedures for the management, transportation and storage of nuclear waste
- Nuclear waste is always contained, never deliberately released
- The nuclear industry has an outstanding safety record with more than 14,000 reactor years of operation over 5 decades

Waste management

- **Low level (operational) waste**
  - short-lived radioactive products: tools, filters, clothing, rags
  - 90% of the waste volume, but containing only 1% of radioactivity
  - incinerated in closed containers, then buried in shallow landfill sites
- **Intermediate level waste**
  - materials that require shielding when handled: control rods, internal components, cladding
  - short-lived radioactive products can be disposed with LLW
  - long-lived go with HLW into geological storage
  - incorporated into cement or an organic solid (bitumen or resin), placed in shielding containers and buried
- **High level waste**
  - fission products and spent fuel, approximately 4% of waste volume
  - vitrified and/or enclosed in copper or stainless steel containers
  - 50 years in interim storage in purpose-built enclosures
  - no deep geological disposal facilities needed yet

Quantities:

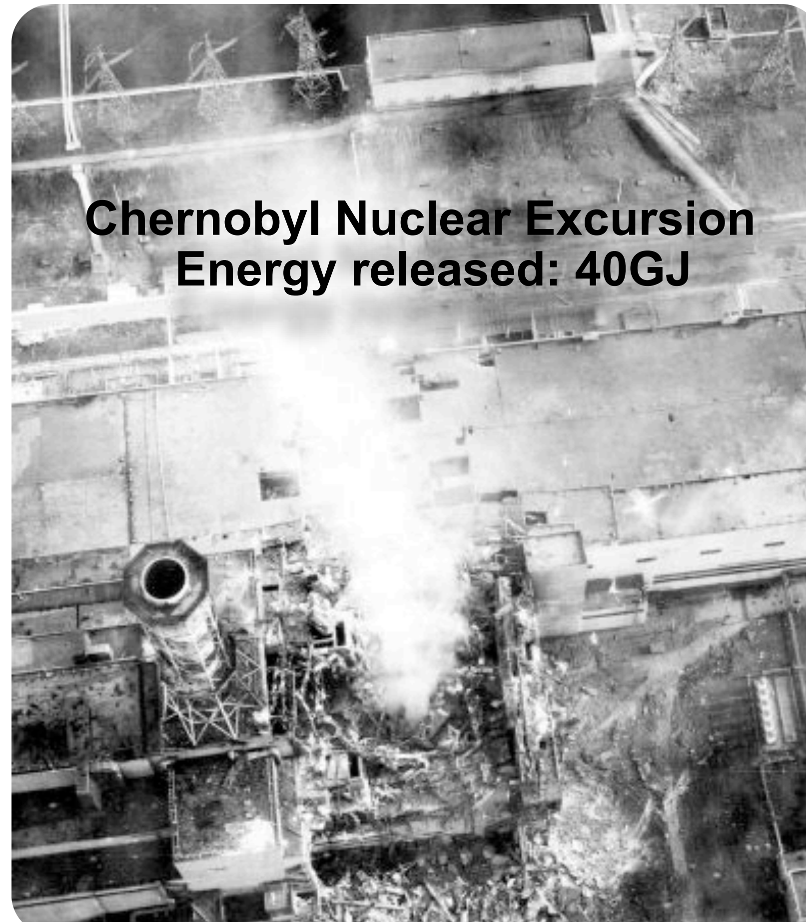
1GWe reactor produces yearly 100m^3 of LLW

3.5m^3 of ILW per year per GWe *or*

70m^3 of ILW per year per GWe if one includes decommissioning

5t of vitrified glass, or ≈12 canisters 0.4m in diameter and 1.3m hight per year per GWe

Nuclear explosion vs. explosion at a nuclear plant



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Other comparisons

Event	Type	TNT Equivalent	Energy released
Tsar Bomba	3-stage Teller-Ulam design Thermonuclear test bomb	50 MT	210,000,000 GJ
Castle Romeo	Thermonuclear test bomb	15 MT	63,000,000 GJ
Chernobyl (one unit) during one year	RBMK-1000 reactor 1 GWe (3.2 GWt)		30,000,000 GJ
Three Mile Island Unit 1 operated one year	PWR reactor 800 MWe		24,000,000 GJ
Fukushima Unit 1 operated one year	BWR3 reactor (GE) 439 MWe		14,000,000 GJ
Peacekeeper	ICBM weapon	10 x 300 kT	12,500,000 GJ
Fat Man (Nagasaki)	^{239}Pu implosion-type bomb	21 kT	88,000 GJ
Little Boy (Hiroshima)	^{235}U gun-type bomb	15 kT	64,000 GJ
Chernobyl	Nuclear excursion accident		40 GJ
Steam explosion at nuclear power plant	Accident		0.1 GJ

Three Mile Island - 28 March 1979, Harrisburg PA, USA

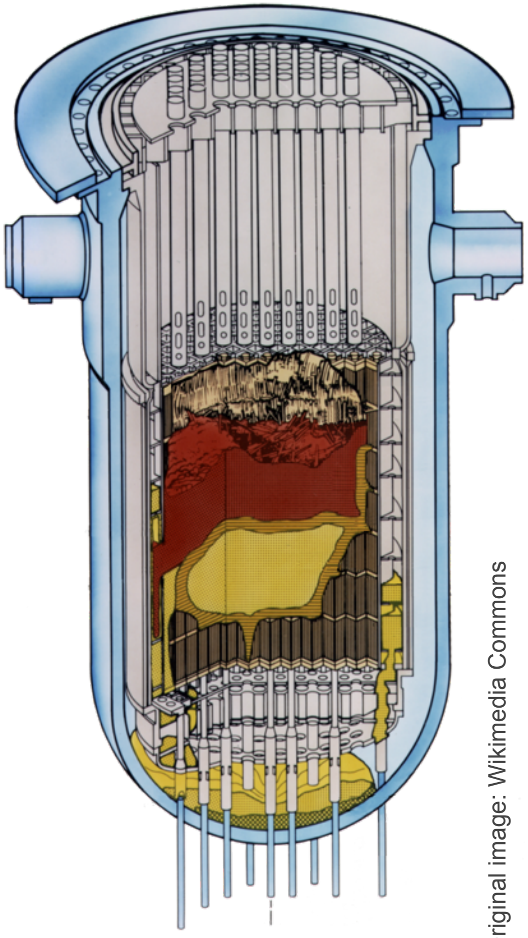
- INES **Level 5** accident at Unit 2
- Accident type: core meltdown
- Deaths: none
- Causes: human error combined with minor equipment failures

Sequence of events:

- 4 AM: For unknown reasons, secondary water circuit pumps stop
- Steam generators stop automatically and reactor performs emergency shutdown (SCRAM)
- Control rods are inserted but core temperature continues to rise due to residual heat
- Auxiliary pumps activate but valves were closed for maintenance
- Core temperature and pressure rise

TMI accident: sequence of events (cont'd)

- Relief valve on the pressuriser tank opens automatically to vent the steam, but fails to close afterwards due to mechanical failure
- Operators are convinced that the valve is shut, because of a design fault of the indicator lamp
- Water in the core vessel starts to boil
- Operators are convinced that the core vessel is overfilled and turn off the emergency cooling pumps
- Around 6 AM, the top of the reactor core is exposed and cladding starts to melt
- The 6 AM shift correctly identifies the situation and takes steps to control it. Emergency is declared at 6:58 AM
- Roughly 16 hours later, the primary loop pumps were turned on again, and the core temperature began to fall
- Years later investigators will find that at about 8 AM, roughly half of the uranium fuel had already melted



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Impact of the TMI accident

- Worst nuclear disaster in the USA
- 40,000 gallons of radioactive waste water was released in the nearby river (an Olympic sized pool contains ≈ 500,000 gallons of water)
- No significant level of radiation was released outside the TMI-2 facility
- Population in the TMI area (≈ 2 million people) were exposed to 1 mrem (a chest X-ray is 10 mrem)
- Ulterior studies found no perceptible effect on cancer incidence; no measurable health effects
- Media coverage was strongly influenced by 'The China Syndrome', a thriller released just 12 days earlier
- The event crystallised anti-nuclear safety concerns among activists and general public
- New regulations were introduced
- The accident contributed to a decline of new reactor construction

Chernobyl - 26 April 1986, Prypiat, Ukraine (USSR)

- INES Level 7 accident at Unit 4
- Accident type: steam explosion, nuclear excursion
- Cause: human error, design flaws
- Death toll varies widely:
  - UNSCEAR 64 (31 directly attributable)
  - WHO 4000

Sequence of events:

- A test aimed to improve safety in case of a power grid failure is scheduled
- Plan is to reduce power from 3.2 GWt to between 0.7 and 0.8 GWt
- Power decreases to 0.5 due to reactor poisoning, and due to operator error drops further, to 0.03
- Operators struggle to increase and stabilise the power, retracting all control rods in the process

Chernobyl: Sequence of events (cont'd)

- The result of all this is that the reactor operates now in a regime very far from its safe design configuration; it is now primed for a *positive feedback* loop
- The planned test is started at 1:23 AM. All along, the automatic control system maintains stability by continuously inserting control rods
- Less than a minute later, the test is finished and - for reasons still unknown - a SCRAM is initiated: all controls rods start to be inserted
- Due to a design flaw of the graphite-tipped control rods, the reactivity in the lower half of the core increases and the power output spikes to about 30 GWt
- A steam explosion occurs, tearing off and lifting the 2,000-ton upper plate
- Fuel rods fracture, control rods are jammed at one-third insertion
- Few seconds later, a second explosion resulting from a *nuclear excursion* dispersed the core and effectively terminated the nuclear chain reaction (other hypotheses: steam explosion or hydrogen explosion)
- A graphite fire starts; large quantities of radioactive contaminants are dispersed
- In some areas, unprotected workers received fatal doses within minutes

Impact of the Chernobyl accident

- Worst nuclear power plant accident in history
- 130,000 people were evacuated, a 30km radius Exclusion Zone is still in effect
- 237 people with acute radiation sickness (ARS), of whom 31 died within months
- 400 times more radioactive material than the Hiroshima bomb, but less than 1% of the radioactive material released by the weapon tests of the 1950s and ‘60s
- 100,000 km² of land was contaminated with fallout, the worst hit regions were in Belarus, Ukraine and Russia, but half of it fell outside the USSR (Sweden, Norway)
- Most dangerous isotopes released were ^{131}I, ^{90}Sr and ^{137}Cs
- 15 deaths from Thyroid cancer were recorded since
- No scientifically significant mutations in animals were documented
- No increase in the rate of birth defects or abnormalities, or solid cancers (IAEA)
- Debate about health effects is still ongoing, many studies done
- Economic cost over the last 30 years estimated at £150 billion