Nuclear Power Economics

Master IGE & ENVIM

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Outline of the course

1. Introduction
2. Nuclear power competitiveness
3. Nuclear waste management
4. Nuclear safety regulation

Statement of purpose

- An overview of nuclear power **economics**
  - Agnostic view on technology choices
  - A descriptive rather than normative approach
- A tool to look at industrial structure and regulatory matters...
  - Does industrial structure influences competitiveness?
  - Does Fukushima calls for nuclear safety regulation reforms?
- ... or the ties between nuclear power development and political or strategic considerations
  - What can economists say about energy technology choices?
  - What about long-term waste management choices?

Definitions: Costs and decisions

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  - e.g. the cost of *doing* something
- Some shortcomings:
  - Accounting for *non-monetary costs*
  - Accounting for attitudes towards risk

Discounting and public evaluation

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- Definition: $\delta = \rho + e \times g$ (Ramsay, 1928)
    - ρ is the rate of preference for the present
    - e is the elasticity of the marginal utility of consumption
    - g is the growth rate of consumption

Risk and uncertainty

Certainty: decision lead to single, certain outcome

Risk: decision may lead to several outcomes described by known probabilities

Roulette wheel, roll of dice, heads or tails

Uncertainty: decision may lead to several outcomes described by unknown probabilities

Horse race, elections, long-term weather forecasts

Incompleteness: decision may lead to unknown consequences

mobile impact on health, drugs side-effects, nuclear accidents...

The enthusiasm of the fifties

1951 First production of nuclear electricity in the U.S.

1953 **Atom for Peace**
US Atomic Energy Act: nuclear knowledge shared

1954 L.L. Strauss: *“nuclear energy is too cheap to meter”*

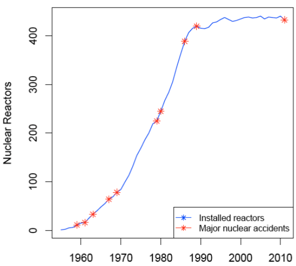
1955 First nuclear submarine (Nautilus)

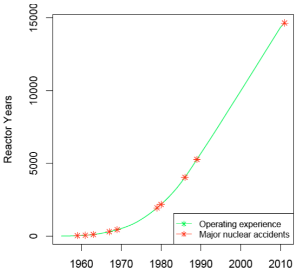
1957 IAEA and Euratom creation
nuclear promotion and technology transfers

1963 GE and Westinghouse compete in the U.S.

Adoption and rise of safety concerns

1973 First oil shock leads to large adoption





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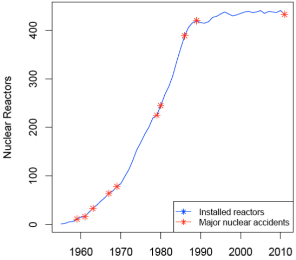
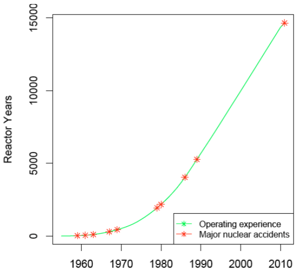




1979 March 28, Three Mile Island (leads to INPO creation)

1986 April 25, Chernobyl accident (WANO creation)

2011 March 11, Fukshima-Daiichi accident

The mid-eighties stagnation

- The rise of safety concerns
  - TMI and Chernobyl disasters
- Drop in electricity demand
  - USSR, France
  - Excess generation capacity
- Oil-price collapse in 1986
- Highly efficient gas turbines technology (GTCC)
- Electricity market and liberalization & privatization

Nuclear power today

- 2014: NP provides 11% of the world's electricity
- World-fleet today: 440 reactors *operable*
  - US: 99
  - EU: 150 (+ 36 in Russia)
  - China: 31
- 60 on-going constructions:
  - China: 20 - EU: 8
  - Russia: 7 - India: 5
  - USA, UAE: 4 - South Korea, Pakistan: 3

Worldwide electricity production (2014)

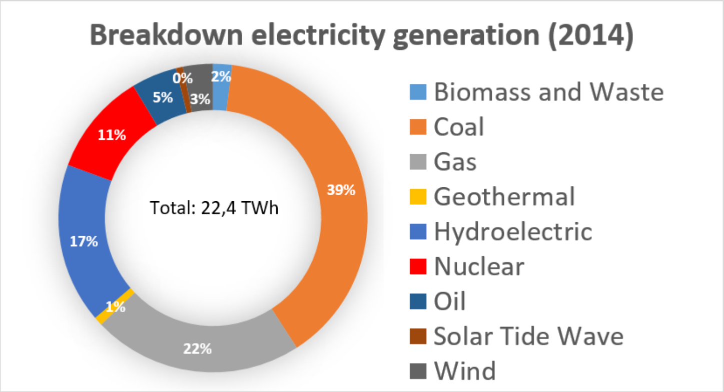


Figure: Source: World Bank & The Shift Project (2016)

Worldwide nuclear production

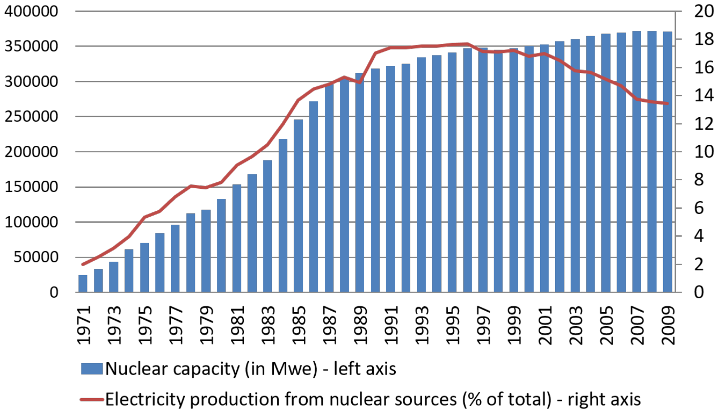


Figure: Source: IAEA PRIS.

Worldwide nuclear fleet (2010)

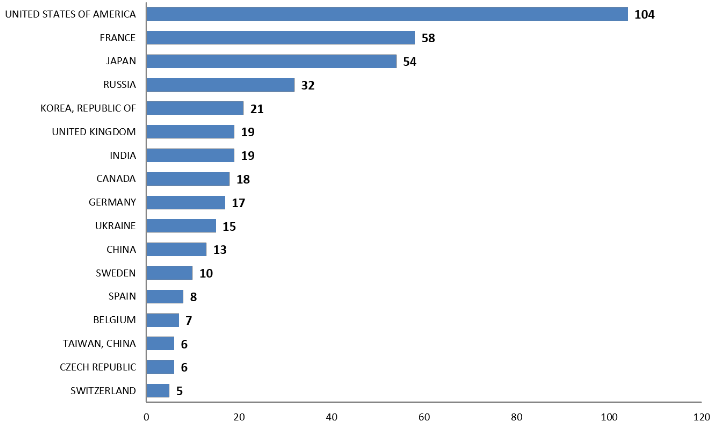


Figure: Source: NEA. 441 total.

Electricity generation mixes

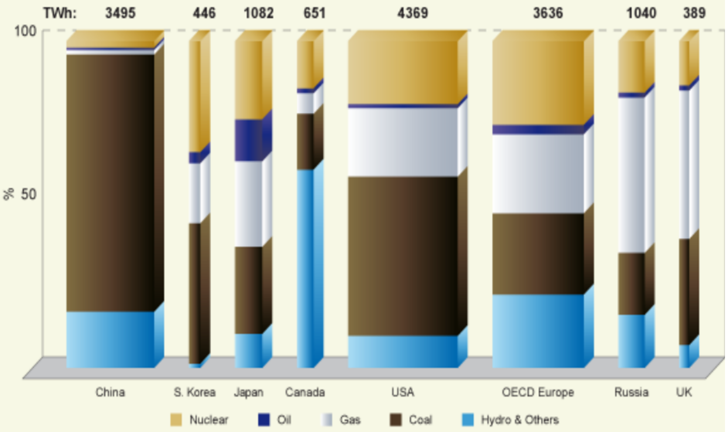
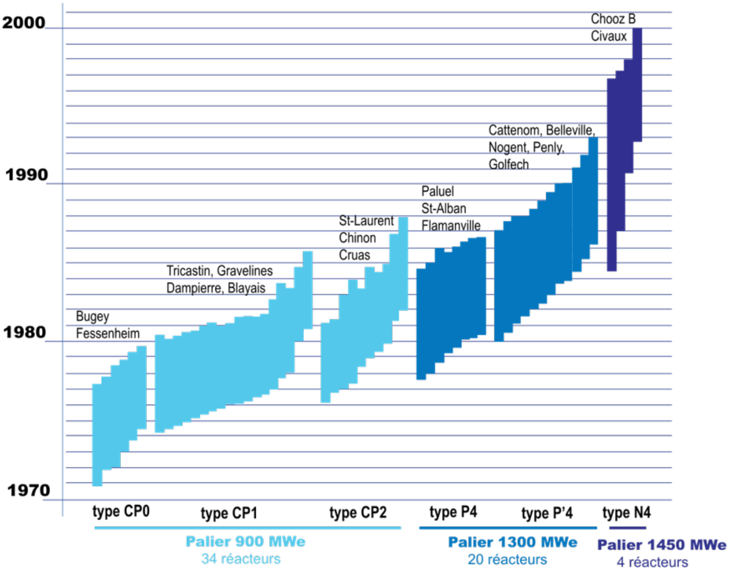


Figure: Source: WNA (2008).

The French fleet



Nuclear technology choices

- **Technology lock-in effect**: increasing return to adoption
  - First: Light water preferred to graphite
  - Second: Pressurized water preferred to boiling water
- Importance of political and strategic considerations
  - on **technology choices**: LWRs are by-products of the US Navy nuclear propulsion program
  - on **program development**: the 1973 oil shock led France to widely adopt nuclear power

Main features of nuclear power economics

Pros

- Cheap **to operate**
- Predictable
- Low carbon emissions
- Security of supply
- Industry development
- Long lifetime

Cons

- High upfront cap. costs
- Long lead times
- Long pay-back periods
- Waste management
- Regulatory/policy risks
- Safety risks

Drivers of nuclear competitiveness

- The competitiveness of nuclear power is driven by:
  - market structures (electricity market & vendor market)
  - competing technologies (shale ?)
  - location (availability of water resources)
  - boundaries
- Competitiveness of nuclear power improves with:
  - rising climate change concerns
  - high fossil fuel prices
  - concerns for security of energy supply (diversification)

The costs of nuclear power generation

- Construction
  - Investment and interest on capital
  - Decommissioning at the end of lifetime
- Fuel
  - Including spent-fuel and waste management
- Operation and Maintenance
- Environmental
  - Accident costs, but also cost of safety regulation
- Security
  - mostly site protection

The levelized cost of electricity (LCOE)

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  - accounts for all aforementioned costs
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- Purpose: compare competing energy technologies
- A discounted cashflow model
  - accounts for all aforementioned costs
  - LCOE = electricity price required to equalize **expected flow of benefits** with **expected flow of costs**
- Heavily depends on the choice of the discount rate
- How to include risk-aversion and non-monetary costs?

Example 1: $\delta = 5\%$

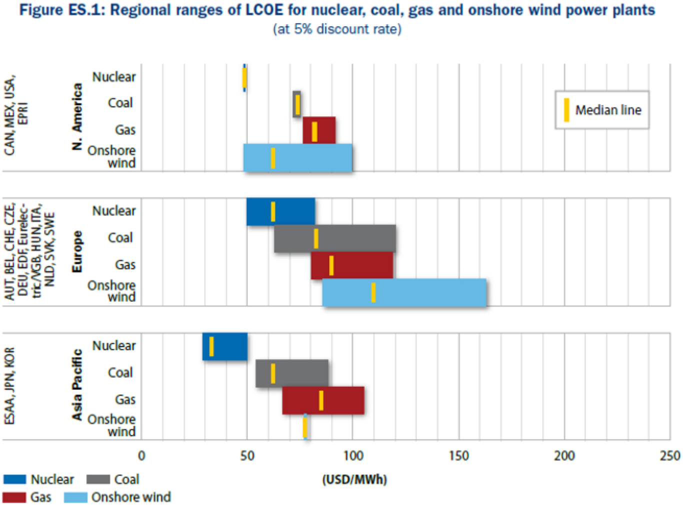


Figure: Source: OECD - NEA (2010)

Example 2: $\delta = 10\%$

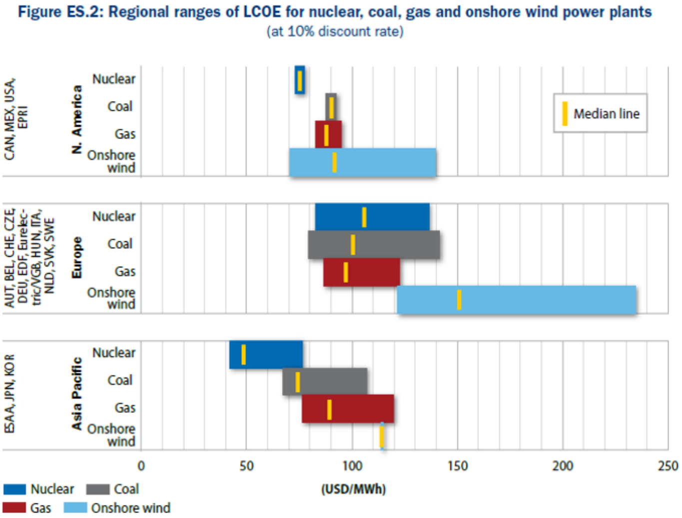


Figure: Source: OECD - NEA (2010)

Key Uncertainties for investors (1/2)

Boundaries what will have to be paid for? (e.g. green land decom.)

Price what assumptions on inflation or exchange rates

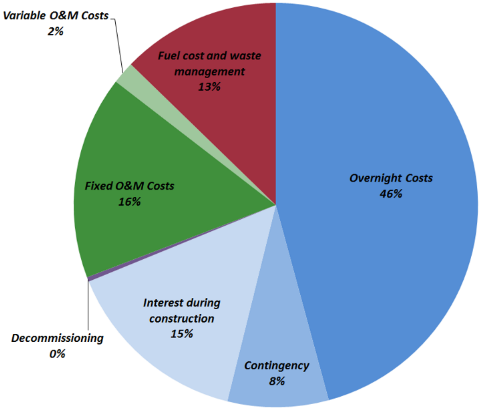
Finance Interest rates and loan guarantees

Market rate-of-return or market price?
existence of a carbon price?

Key Uncertainties for investors (2/2)

Project	completion risk (e.g. Austria)
Location	grid development
Workforce	competition for nuclear skills new entrants vs. leaders
Supply	bottlenecks for large components(pressure vessel)
Regulation	licensing procedure for site/design liability cap

Nuclear cost breakdown (NEA, 2015)



- 7% discount rate:
  - 70% capital costs (up-front)
  - 15% variable costs
  - Decommissioning is dwarfed by interest rate
- At 3% - Cap. cost = 50%

A focus on construction costs

- Important because of their share in the LCOE of nuclear power
- Historically, an upward trending slope
- Increases due to:
  - safety upgrades...
  - ... but also lack of standardization
- Evidence from the U.S. and OECD, not necessarily true in Asia
- Decommissioning remains uncertain
  - predictions between 300M€and 1b€
  - strong economic incentives to delay decommissioning

Evidence from the U.S. and France

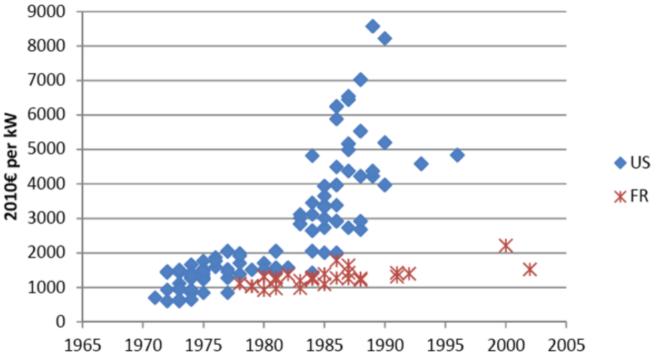


Figure: Source: Rangel and Lévêque (2014)

Evolution of lead-times

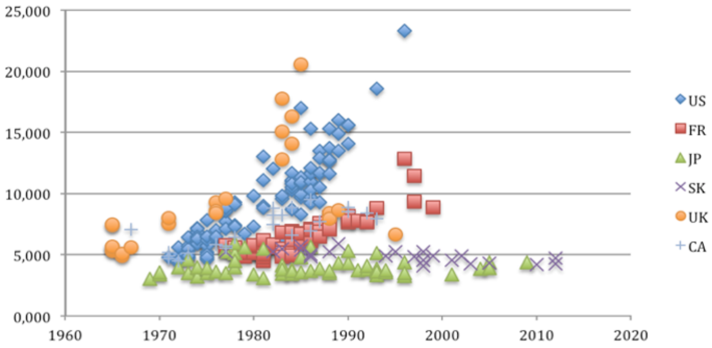


Figure: Source: OECD and Rangel (2014)

Curbing the cost-increase curse

- Which levies for the nuclear industry?

- Learning-by-doing
  - Replication of same design, by same workforce, in same setting
  - Cost sharing when multiple units located on unique site
  - Industrial structure matters: spillovers within vendors
  - trade-off between concentration and competition

- Economies of scale
  - standard argument, but unclear for nuclear power
  - larger volumes lead to higher stress, water pressure, irradiation...
  - lead to new requirements (materials), longer lead-times, lower reliability...

Liberalized electricity markets

- Features that impede NP competitiveness in LEMs
  - Large upfront cap. investment with long lead-time
  - Lack of recent experience in construction
  - Project subject to political and regulatory challenges
- Two major questions:
  - Can nuclear projects be financed in liberalized markets?
  - Can nuclear operators and vendors adapt to competitive environments?

Competition in liberalized markets

- Barriers to competition arise when:
  - There is a single nuclear power operator
  - Share of NP in elec. production is large
  - Nuclear generation from existing plants is cheap
  - Market entry is difficult and baseload competition is weak

- Possible remedies (public policies)
  - Regulating access: the French case
  - Regulating wholesale prices: the South-Korean case
  - Regulating production: divestiture of nuclear assets

The French case

- The French electricity generation sector
  - Nuclear power produces 75% of the French electricity
  - Its price is regulated by the Government

- EU Commission wants more competition in the electricity market but...
  - Price is below european market price
  - Divestiture is excluded due to safety concerns

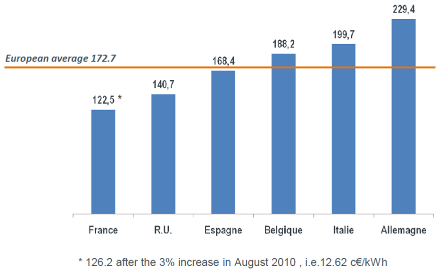


Figure: Percebois (2012)

The French paradox (1/2)

- Low prices prevent new entrants from entering the market

- Promoting competition:
  1. Regulate price to match EU market prices
  2. Induce competitors to match the French prices

- The French paradox:
  - Usually competition lowers prices
  - Here prices have to go up to promote competition

- Both policies can be costly
  - Case 1 would require taxation of EDF's **scarcity rent** induced by the increasing prices
  - Case 2 would require subsidies to promote entry in spite of low prices

The French paradox (2/2)

- Two contradicting goals for the French policy-makers
  - Allow consumers to benefit from the perks of nuclear power, which they financed
  - Comply with the EU guidelines and allow new entrants to win market shares from incumbent EDF

- Three solutions considered
  - Price deregulation: would lead to increasing prices (social acceptance)
  - Levy of the nuclear rent through taxation and redistribution
  - **Share the nuclear rent**: allow competitors to source from EDF's nuclear power at a fixed tariff

The nuclear fuel cycle

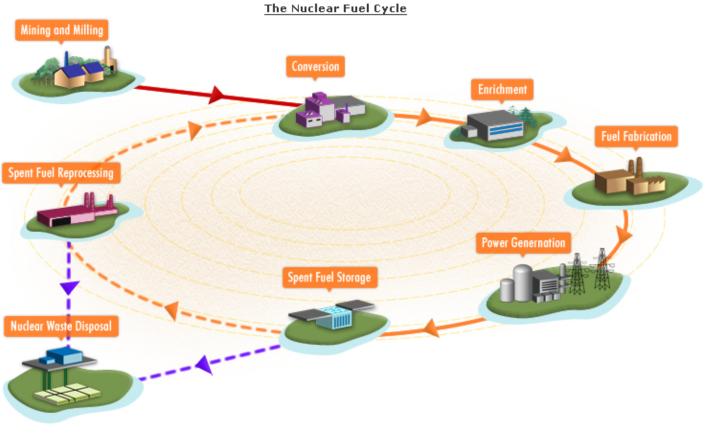


Figure: Source: Google image

Radioactivity and nuclear fuel

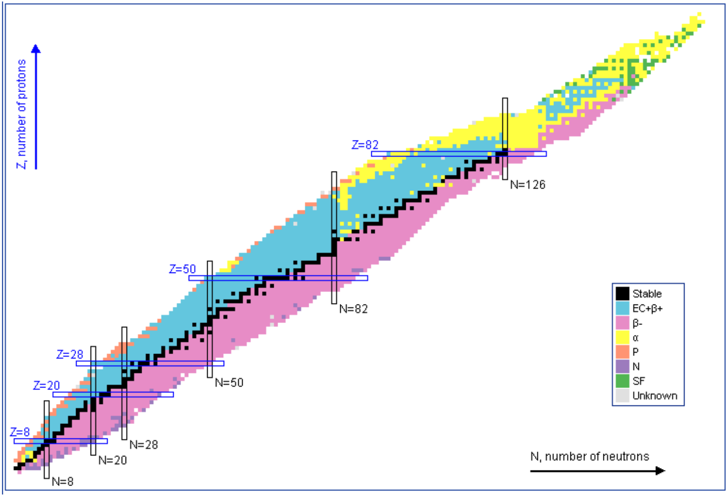


Figure: Source: Google image

Major features

- Nuclear waste include various fission products
  - Low and medium level waste: 95% of volume, 5% of activity
  - Fission products: not recyclable, long-lived, hot (T and A)
  - ^{239}Pu: large half-life (20.000y), but recyclable

- On-site temporary storage
  - Not a long-term solution, additional risks
  - Long-term solutions meet social and technical barriers
  - Equity concerns go beyond the scope of economic analysis

- Several technological choices:
  - Open fuel-cycle with long-term repositories
  - Closed fuel-cycle with LT rep. and reprocessing

Open fuel-cycle (once-through)

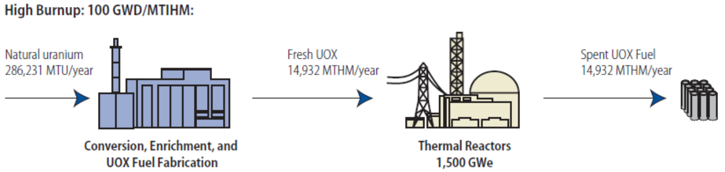
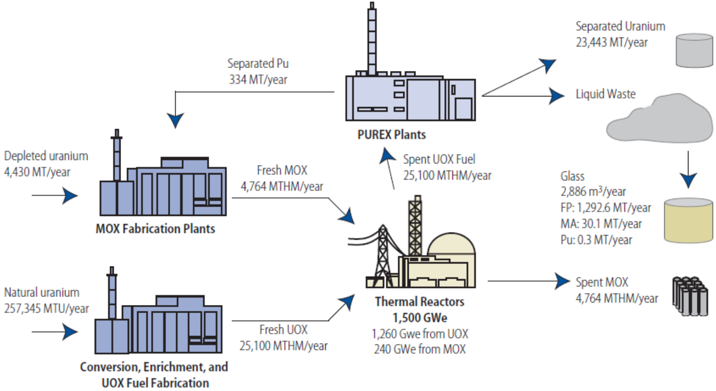


Figure: Source: MIT (2011)

Closed fuel-cycle (Pu recycle - MOX - one recycle)



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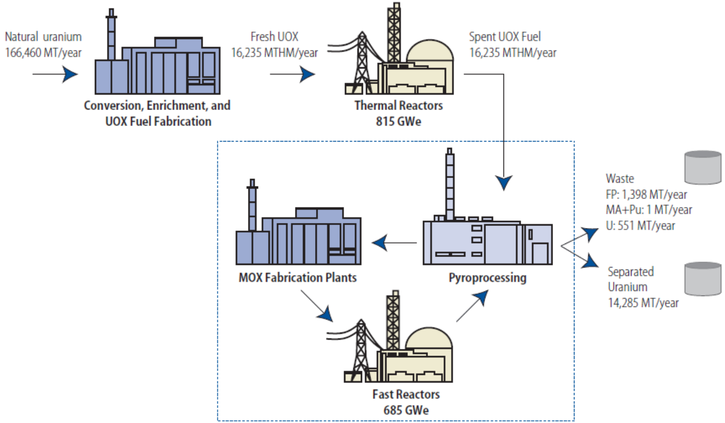
Closed fuel-cycle (Pu recycle - MOX and FBR)



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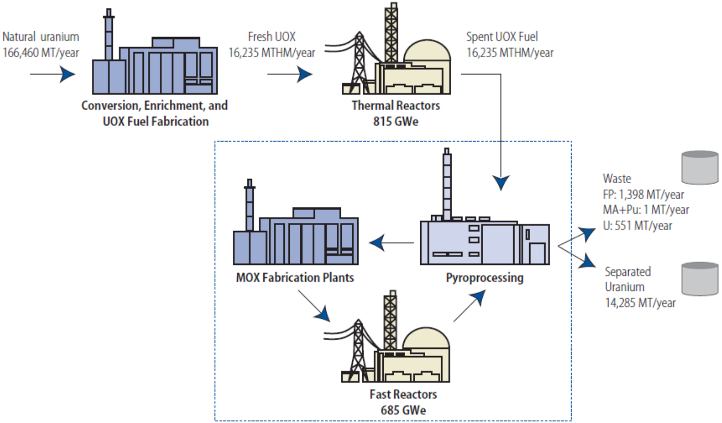
Technology and resource availability



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Which option to choose?

- MIT (2009, 2011) suggests that open fuel cycle is best:
  - better in terms of safety/proliferation
  - despite more waste than closed fuel cycle
  - positive option value: more R&D needed
- Harvard (2003): Price of Uranium for FBR option to be competitive is 340€/kg, instead of 60€/kg today
- MOX option not economical (Ko and Go, 2012)

Main features of nuclear decommissioning

- Five reactors have already been decommissioned worldwide
  - Research or small commercial reactors
  - Few information regarding the future
- Main issue: how long can we wait?
  - waiting increases the risks of radioactive contamination
  - but also reduces the cost of decommissioning
  - trade-off between social acceptability and cost-effectiveness

Cost of past decommissioned reactors

Plant location	Electrical power	Closure date	current status	Cost (M€2014)	Source
Shippingport (USA)	60 MWe	1989	completed	163	OSTI
Yankee Rowe (USA)	185 MWe	1991	completed	608	Wikipedia
Maine Yankee (USA)	860 MWe	1996	completed	668	EPRI
Connecticut Yankee (USA)	590 MWe	1996	completed	821	Wikipedia
Tokai 1 (Japan)	160 MWe	1998	expected in 2018	780	NEA, 2003
Brennilis (FR)	70 MWe	1979	in Phase 3	546	CDC
Windscale (UK)	32 MWe	1981	completed	117	WNI
Coarso (IT)	840 MWe	1987	expected in 2017	750	SOGIN

Size of reactors in shut-down state in the EU

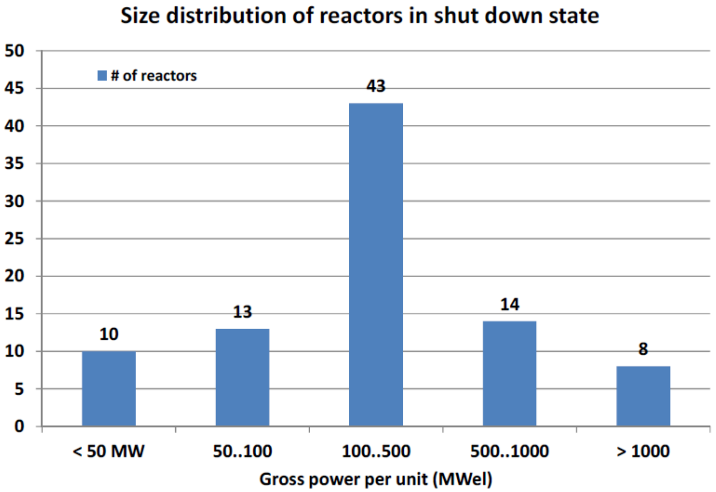

Figure: Source: IAEA

Design of reactors in shut-down state in the EU

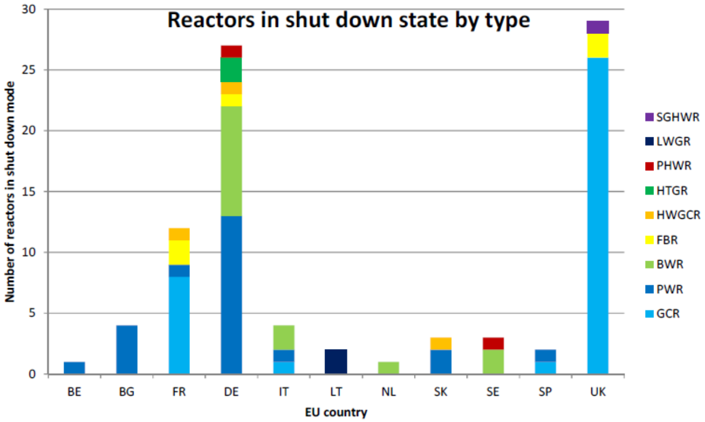

Figure: Source: IAEA

The uncertainties of decommissioning

- *Ex ante* decision-making
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  - Raises intergenerational justice issues
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- Implementation
  - Accelerated schedules
  - Increased safety requirements
  - Availability of storage
  - Management of nuclear skills and know-how

Safety from the economic lens

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  - Firms face only limited consequences of their activity
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  - examples: pollution abatement, workplace safety, airline safety...

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- At what cost?
  - Adverse selection: firms know the risk better
  - Moral hazard: regulators imperfectly observe the firms' actions
  - Limited liability: firms are never fully liable

Features of nuclear safety

Damage nuclear accidents are dreadful

Insurance does not work (Laffont, 95)

Frequency accidents are hopefully too rare to measure their probabilities

how to account for this uncertainty?

Reputation A major accident impacts the industry worldwide

Calls for international governance

Technology Quantitative safety objectives are costly to define in complex technological systems

Estimated risks

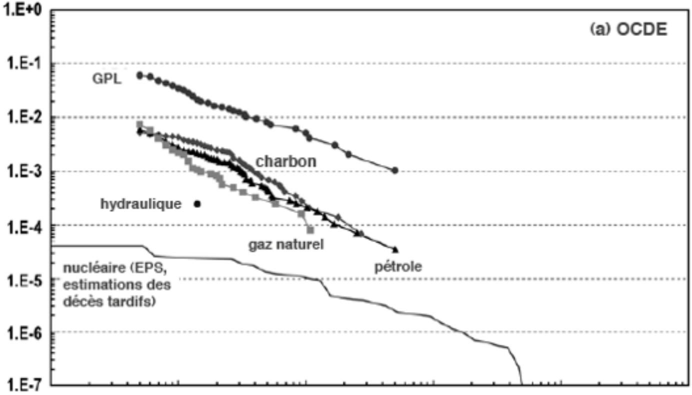


Figure: Source: OECD - NEA (2010)

Perceived risks

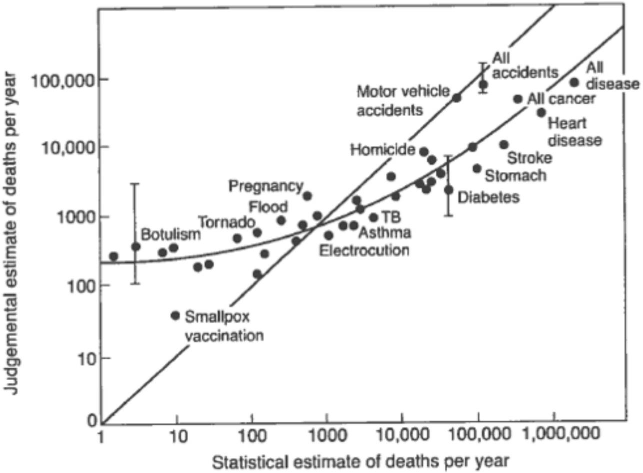


FIG. 2.1 Perceived versus Actual Mortality Risks
Source: Fischoff *et al.* (1961), p. 29.

Estimated external costs

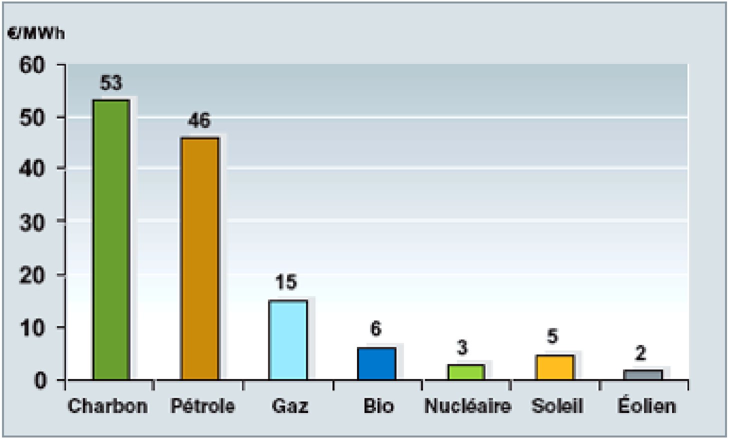


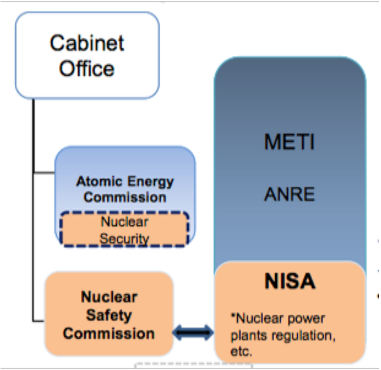
Figure: Source: ExternE (1999)

Safety Governance and regulatory capture

- Regulatory governance
  - Coordination between regulations (econ. vs. safety)
  - Self-interested Regulators/judges (career concerns)
- The Regulatory capture theory
  - Firms may want to bribe regulators to be more lenient
  - Government wants to minimize the risk of capture
- Several governance issues and solutions
  - Forbid personnel transfers
  - Separate judges from regulators
  - Limit the regulators' discretionary power

The case of Fukushima Daiichi (1/2)

- Primary cause: Earthquake + tsunami
- Secondary cause: bundled nuclear promotion and safety regulation, leading to:
  - Collusion between reg. and operator
  - Poor choice of safety standards
  - Falsifications



The case of Fukushima-Daiichi (2/2)

- An existing insufficiency in the design
  - planned to resist earthquake of 7.9 and wave of 6 meters
  - 11 March 2011: earthquake 9 and wave over 10m
- An under-estimation of the risks
  - Existence of documentation on such earthquakes and waves
  - Proofs that Tepco and Regulator knew this documentation, but ruled it out
- A failure to adapt on time
  - On the 8th of March, Tepco signals the possibility of a 10m wave
  - Based on an internal note from 2008, deemed unrealistic at the time

The need for international governance

- Fukushima reveals new information regarding safety
  - Importance of regulatory independence and transparency to avoid capture
  - Many countries and industry affected...
  - ... but not all countries have integrated this new information
- A need for international safety governance
  - More stringency from IAEA to limit the external impact of bad firms/regulators on safe firms/regulators
  - to account for cross-border effect in nuclear policy decisions
  - Yet, need to avoid blocking position risks...

Conclusion (1/2)

- The future of nuclear power will depend on the ability of vendors and operators to reduce the construction costs of nuclear reactors
- Discounting dwarfs the importance of waste management and decommissioning in energy policy decisions
- Nuclear safety is not only technical, as its efficiency is determined by the quality of the institutional design

Conclusion (2/2)

- A utility that chooses nuclear power faces several risks
  - uncertain competitiveness
  - uncertain policies based on perceptions
  - uncertain safety measures due to events taking place very far
- Two very different issues for the future:
  - What is to become of existing nuclear power stations?
  - Should new stations be constructed?

Many other interesting topics...

- Political economy of entry and exit policies
- The role of governments in the international trade of nuclear technologies
- Option value of nuclear R&D: nuclear fusion, fast-breeder...
- Market instruments for nuclear insurance (cat. bonds)

Readings and resources

- Books:
  - *The economics and uncertainties of nuclear power*, F. Lévêque, Cambridge University Press, 2015
  - *Economics of nuclear power*, G. Rothwell, Routledge, 2015
- Research papers in specific topics in nuclear economics:
  - Feel free to ask (romain.bizet@mines-paristech.fr)
- On-line resources:
  - data on energy: The shift project
  - International agencies: IAEA, OECD-NEA, WNA

Back-up: Fission and by-products

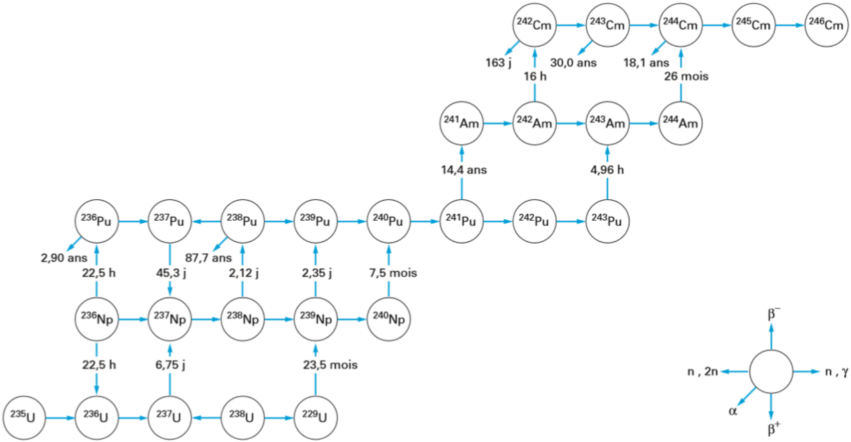
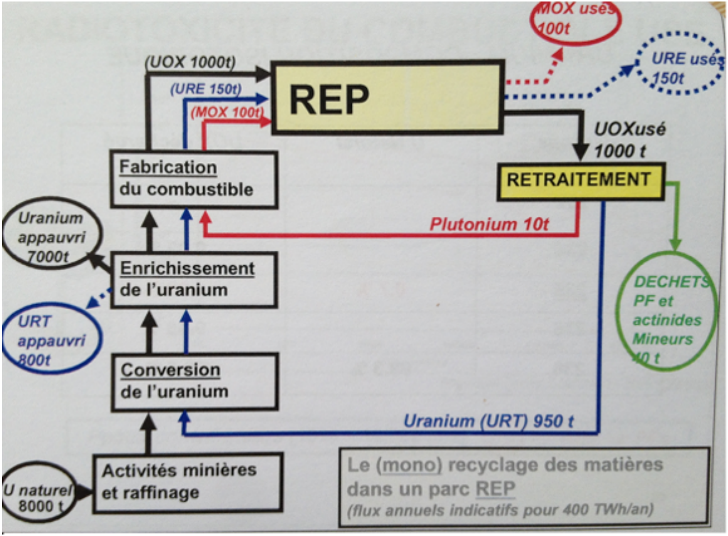
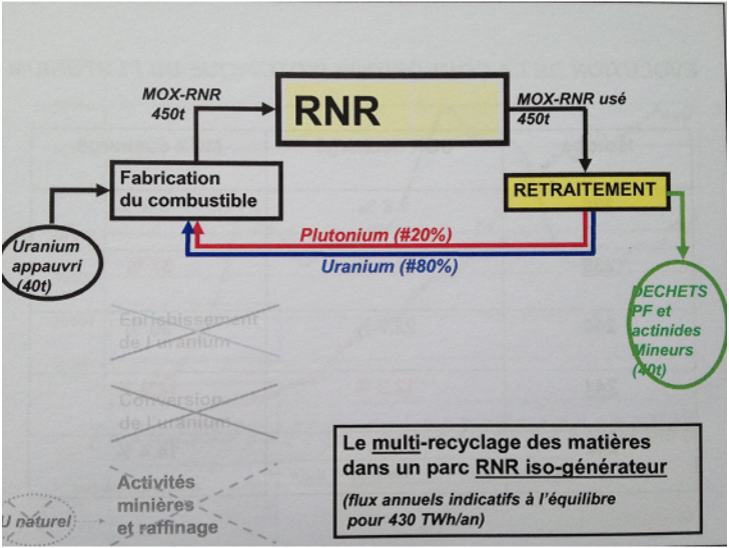


Figure: Source: Zaetta, 2004

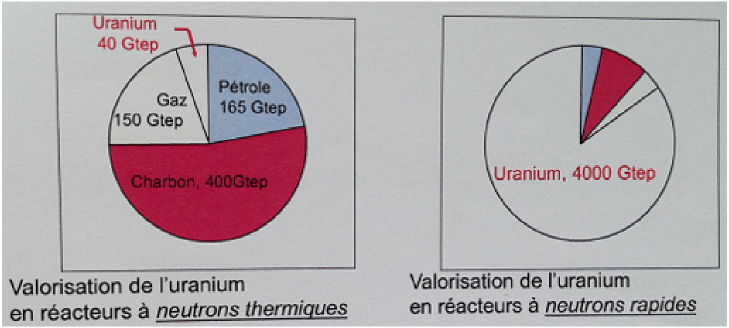
Back-up: Uranium need with PWR



Back-up: Uranium need with FBR



Resource management



Back-up: The French NFP case