# The Cost of Nuclear Electricity
# France after Fukushima

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# French Background on Nuclear Power

- 1957 Broad political support for Civil Nuclear Power
- 1986 Political Backlash after Chernobyl Catastrophe
- 2006 Nuclear Transparency Act, Nuclear Security Agency
- 2011 Fukushima Disaster, Nuclear Economic Audit
- 2012 Cour des Comptes report, “Open Data Victory”

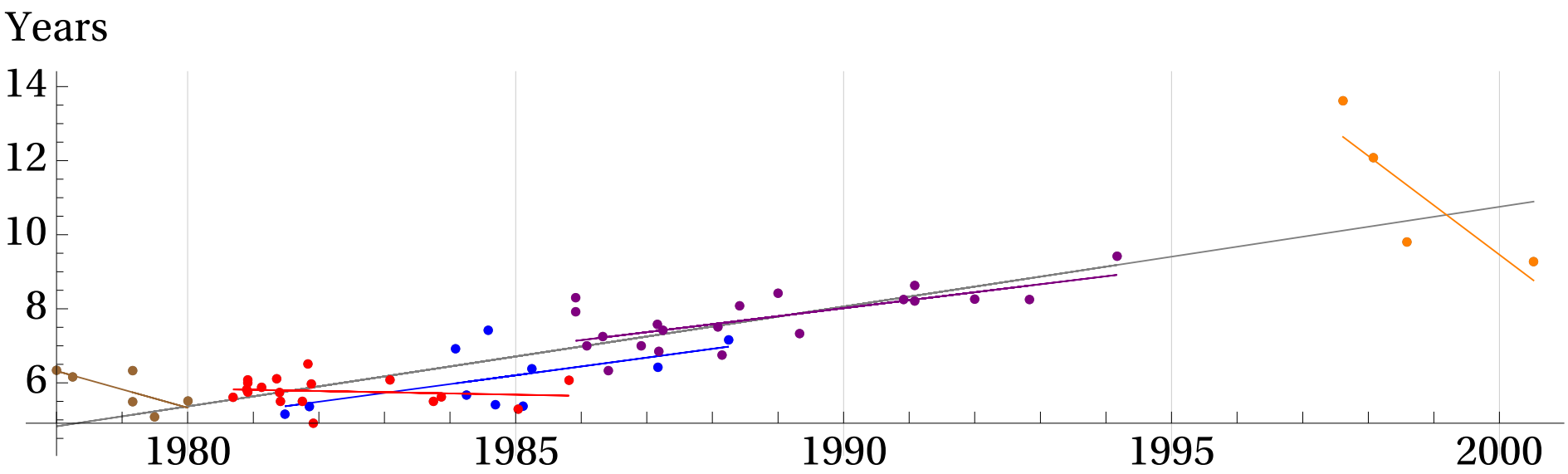
- First Generation reactors, closed and in dismantling
- Focus on Second Generation starting 1970s

# Scaling Up Nuclear Power

- 1966 General *de Gaulle* opposed to US “meddling”
- 1967 EDF bypasses government prohibition in Belgium
- 1969 *de Gaulle* resigns, quickly 6 reactors order (CP0 batch)
- 1974 oil shock, order for 18 identical reactors (CP1 batch)
- 1976 further 18 reactors order (CP2 & bigger P4 batches)
- 1980 8 reactors (P’4 batch)
- 1984 4 fully French reactors (N4 batch)
- Each successive batch more sophisticated
- Long lasting investments: *Steam Trains* alongside *TGVs*

# French Second Generation Nuclear Reactors

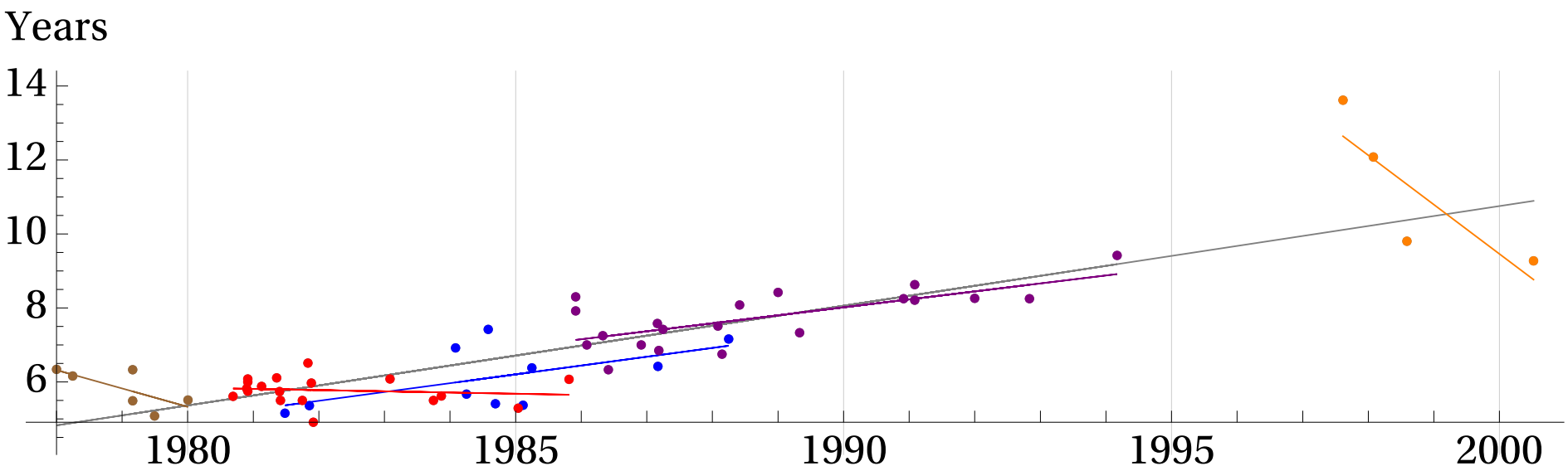
- Construction duration of 58 French nuclear reactors
- Function of the date of commercial operation
- Distinct colors and linear fittings for the five batches
- Source: PRIS database, International Atomic Energy Agency



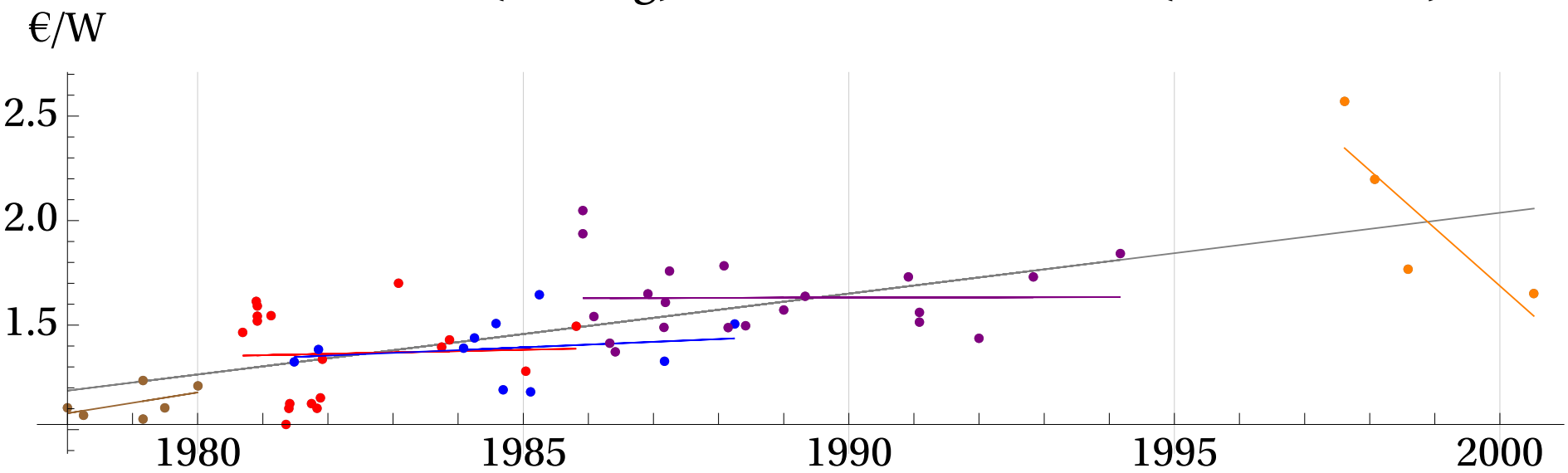
# Evolution of Plant Cost for Second Gen. Reactors

- Current knowledge: Grubler, 2010, Energy Policy
- Based on 2000 report by MPs Charpin, Dessus & Pellat
- No plant information, only series of yearly EDF investments
- *Negative learning-by-doing for French nuclear power scaling up*
- New information source: 2012 Court of Audit report
- Capital cost 29 plants, historic expenses on everything else
- Correlation *unit cost* vs. *construction time*: 80% (plants)
- US reactors: 76% correlation $\Rightarrow$ strong duration–cost link
- Estimate reactor capital cost using duration and plant cost

# Construction Cost of Second Generation French Nuclear Reactors




Old information (Timing) vs. New information (2010€ cost)

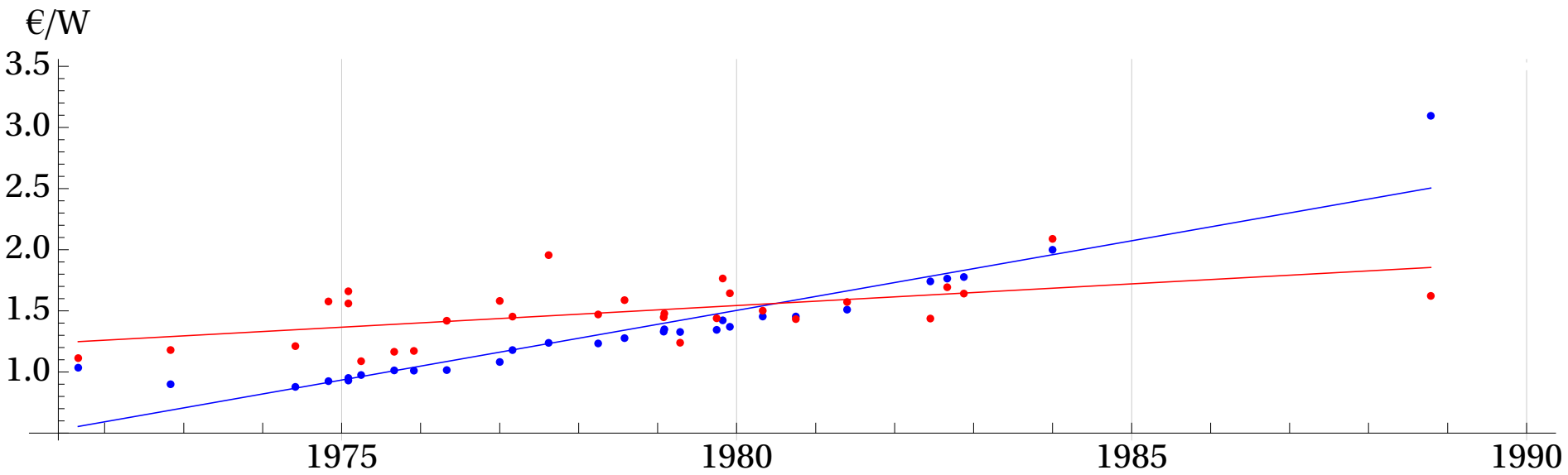


# Comments on Capital Cost Evolution

- Average cost 1524 €/kW
- Limited cost escalation: grows at 2.1%/year or 30 €/kW/year
- 48 Westinghouse reactors, build in 13 years, cost growth 1.4%/year
- Contrast with US: 100 reactors, cost grew at 19%/year
- Success clues: standardization, strong focused public monopolies
- EDF leadership: OEMs, Streamlined building, Dam Experience
- Latest fully French reactors: slower, costlier
- Possible large "learning curve" but limited to just 4 reactors
- French nuclear program: industrial success, too ambitious economics
- Oil shocks $\Rightarrow$ killed expected demand growth
- Full economic benefit requires European output market

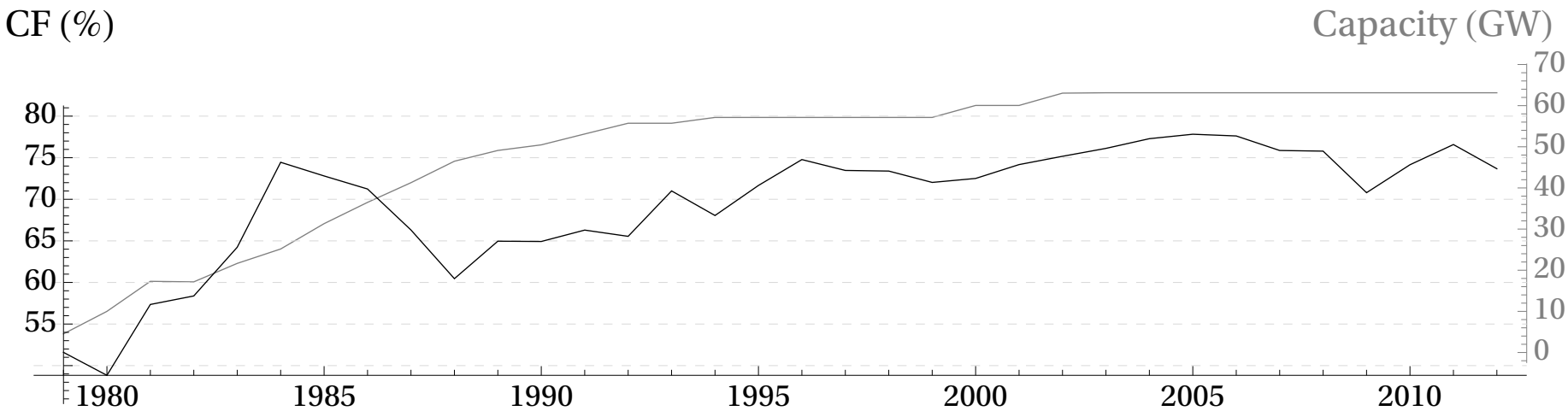
# Comparison with Grubler

- Grubler vs. Court of Audit (timing is construction start)
- Plant Unit Cost escalation increasingly off the mark
- Mean cost 1.4 €/W, growth 8.4%
- Real: 1.5 €/W, growth 2.1%



# Availability & Capacity Factor

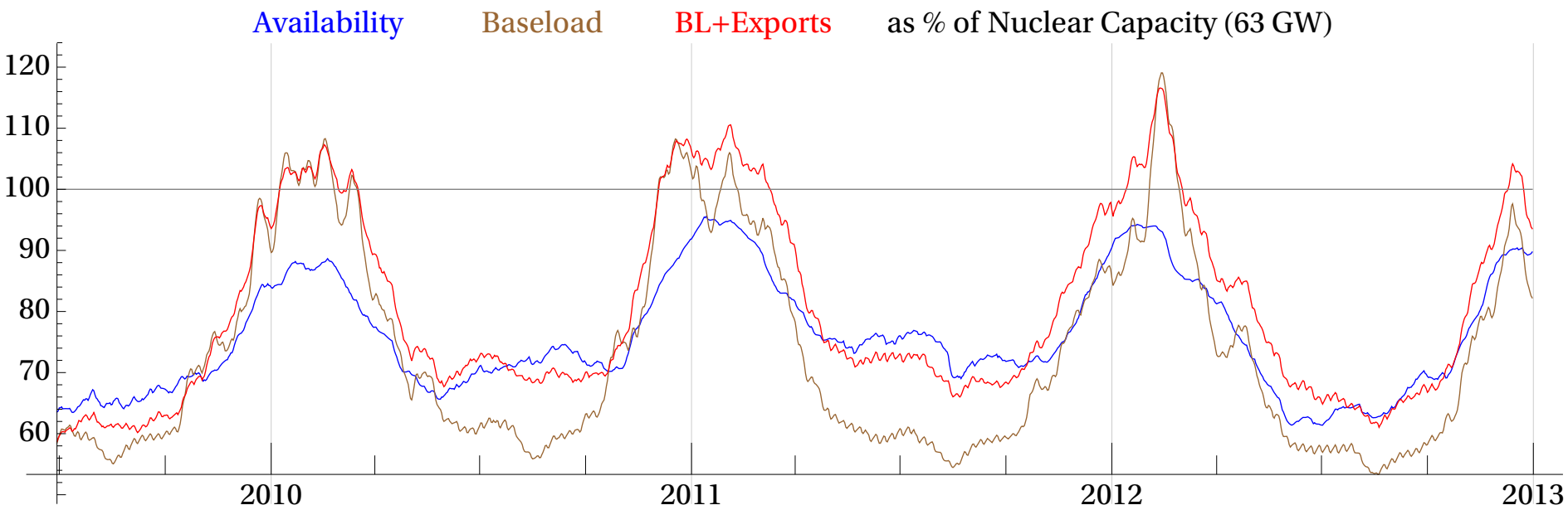
- Capacity Factor: ratio of actual output to theoretical maximum
- French nuclear power capacity: steady at 63.1 GW since 2002
- Average yearly output of 418 TWh, $CF = 76\%$




- One in every four reactors is off at any time
- French CF far below the industry consensus at 90%
- EDF points to lack of maintenance investments around 2000
- What about 1990s with young “problem-proof” fleet ?

# Eliminate Market Based origin of low CF

- Could lack of demand forces EDF to keep idle capacity ?
- Fleet availability (TSO daily report): 95% during winter peak




- Below 70% in summer coincident low national demand
- Profitable export for nuclear surplus during summer
- High correlation between daily availability and daily net exports
- EDF would increase CF during summer if it could do so

# Fleet Costing: Investment

- Court of Audit (2012) report goes back to 1957
- Seeks all items relating to civilian nuclear power
- Monetary figures actualized to €2010 to account for inflation
- Investment cost for French Second Generation Nuclear Reactors
- Construction + Engineering expenses = Overnight Cost
- Slow Construction: interest paid to creditors accounted for
- Total Plant Investment for French Second Generation Nuclear Plants

| *Investment* | bn€ | €/kW |
|---|---|---|
| Construction | 72.9 | 1154 |
| Engineering | 10.3 | 163 |
| Financing Costs | 13.0 | 207 |
| **Total** | 96.2 | 1524 |

# Fleet Costing: Fuel

- Uranium fuel cycle: 3 stages

**1** Front-end: extraction, conversion and enrichment

- Bought from AREVA under "cost plus" agreement, stable

**2** Enriched uranium burnt in reactors during 4 years

**3** Back-end cycle: 12 years of cooling in pools, recycling, storage

- Continuous flow of spent fuel = operating expense

| *Fuel* | bn€/year |
|---|---|
| Acquisition | 1.5 |
| Spent fuel | 0.9 |
| Stock | 0.6 |
| **Total** | 3.0 |

# Fleet Costing: Operation & Maintenance

- Source: EDF accounts for 2008, 2009 and 2010
- Maintenance = one cost + one investment
- Labour = wages + employees perks
- Support = central services + taxes + research + financial cost
- Fukushima: special investment for security and reliability

| *O&M* | bn€/year |
|---|---|
| Maintenance | 3.8 |
| Labour | 2.7 |
| Support | 3.4 |
| Fukushima | 2.0 |
| **Total** | 11.9 |

- O&M cost $\approx 4\times$ fuel cost (similar to RES)

# Fleet Costing: Dismantling

- Dismantling of power plants at the end of their operating life
  - 10 years phase of deconstruction
  - 15 years waiting period
  - 10 years phase of site restoration
- Cost estimate: complicated exercise, discounting issue
- EDF's dismantling cost estimate: lowest among international peers
- Sole experience "Maine Yankee" in US: twice EDF's estimate
- Worst case scenario to account for variability: double cost
- CEA research institute part of French Nuclear package
- Numerous facilities, some already in dismantling
- Last Cores: non irradiated fuel inside the reactor at shutdown

# Fleet Costing: Waste Management

- Waste management: infinite duration (economically speaking)
- Deep geological disposal: highly uncertain undertaking
- Producers estimates: twice Waste Management Agency
- Back-end Cycle cost decomposition

| *Back-end* | bn€ | €/kW |
|---|---|---|
| Dismantling EDF | 18.4 | 291 |
| Dismantling CEA | 1.9 | 30 |
| Last cores | 3.8 | 60 |
| Waste EDF | 23 | 365 |
| Waste CEA | 2.4 | 38 |
| **Total** | 49.5 | 784 |

# Fleet Costing: Back-end Cycle

- Levelized cost: Back-end cost 50 bn€ but 40 years from now
- Provisions for the future: $\frac{r}{(1+r)((1+r)^{40}-1)}$ of the requirement
- EDF and AREVA use a nominal 5% i.e., 3% in real terms
- Public choice 2% real interest: provision at 1.6% or 0.8 bn€/year
- Nuclear energy: blackswan (low but not zero risk, high damage)
- Premium covering 100 bn€ damages: 4 bn€/year
  - 2005 Hurricane Katrina economic damage: 100 bn€
  - 2011 Japan Earthquake economic damage: 160 bn€
  - Fukushima clean-up: 20 bn€ (site) + 20 bn€ (surroundings)
- US: most stringent insurance requirements (Price-Anderson Act)
- Market quote to US operators = $\frac{1}{100}$ French hypothetical quote

# Fleet Costing: Development Cost

- Deployment nuclear sector preceded by major research programs
- R&D: 1 bn€/year, 1957–2010

| *Development* | bn€ |
|---|---|
| R&D 1st gen | 14.4 |
| R&D 2nd gen | 20.0 |
| R&D 3rd gen | 21.0 |
| SuperPhénix | 12.0 |
| Old Reactors | 6.1 |
| Dismantling | 3.9 |
| **Total** | 77.4 |

- Dev. cost spread over cumulative power output 1968–2010
- Levelized *developmental cost*: 7.7 €/MWh

# Fleet Costing: Summary

- French rate for publicly financed energy investments: 4.5%
- Worst Case: 2× future cost & 10% rate for investor owned business
- Annuity (capital recovery factor): 5.8% or 10.2%
- Levelized Cost of Second Generation French Nuclear Power

| *French PWR* | *Best* | | | *Worst* | | |
|---|---|---|---|---|---|---|
| Item | bn€/y. | €/kW/y | €/MWh | bn€/y. | €/y./kW | €/MWh |
| Capital | 5.6 | 89 | 13.4 | 10.9 | 172 | 26.0 |
| O&M | 11.9 | 188 | 28.5 | 11.9 | 188 | 28.5 |
| Fuel | 3.0 | 48 | 7.3 | 3.0 | 48 | 7.3 |
| Back-end | 0.8 | 13 | 1.9 | 1.6 | 25 | 3.8 |
| Insurance | | | | 4.0 | 63 | 9.6 |
| Development | | | 7.7 | | | 7.7 |
| Total | 21 | 338 | **59** | 31 | 497 | **83** |

# Levelized Cost of French Nuclear Power: Comments

- Low 76% historical availability of reactors weights negatively on cost
- Best case: O&M $>$ 50% yearly cost, dwarfs capital cost
- EDF efficient plant builder, poor user
- Worst case: all items meaningful, high cost (to French people)
- Gvt. nuclear electricity tariff 42 €/MWh (vs. 59 here)
- Main difference: past investment heavily amortized already
- French customers "overcharged"
- Different horizon: gvt. discards both past and distant future
- Comparison with Grubler in €/MWh
- Court of Audit information double previous levelized cost estimate

| Item | Capital | O&M | Fuel | Back-end | Development | Total |
|---|---|---|---|---|---|---|
| Grubler | 12.5 | 6.0 | 6.3 | 2.5 | 3 | 30 |
| Auditors | 13.4 | 28.5 | 7.3 | 1.9 | 7.7 | 59 |

# Future Cost of Nuclear Electricity in France

- Previous findings relate to a past technology
- Flamanville EPR full cost $\frac{8.5}{1.6} = 5312$ €/kW
- No development cost, improved availability 85%
- Other items: identical since inertia of EDF's culture
- Two scenarios as before for Levelized Cost of EPR

| *EPR* | *Best* | | | *Worst* | | |
|---|---|---|---|---|---|---|
| Item | bn€/y. | €/kW/y | €/MWh | bn€/y. | €/y./kW | €/MWh |
| Capital | 19.5 | 310 | 41.6 | 34.3 | 543 | 73.0 |
| O&M | 11.9 | 188 | 25.3 | 11.9 | 188 | 25.3 |
| Fuel | 3.0 | 48 | 7.3 | 3.0 | 48 | 7.3 |
| Back-end | 0.8 | 13 | 1.7 | 1.6 | 25 | 3.4 |
| Insurance | | | | 4.0 | 63 | 8.5 |
| Total | 35 | 559 | **76** | 55 | 869 | **117** |

- 2013 UK EPR deal: 108 €/MWh for 35 years to EDF

# Comparisons: US vs. FR

- Large literature, Koomey & Hultman (2007)
- US vs. FR Nuclear Cost: capital cost $3.4\$/W \approx 2\times$ French value
- US-FR PPP exchange rate of 2010 at 1.15 \$/€

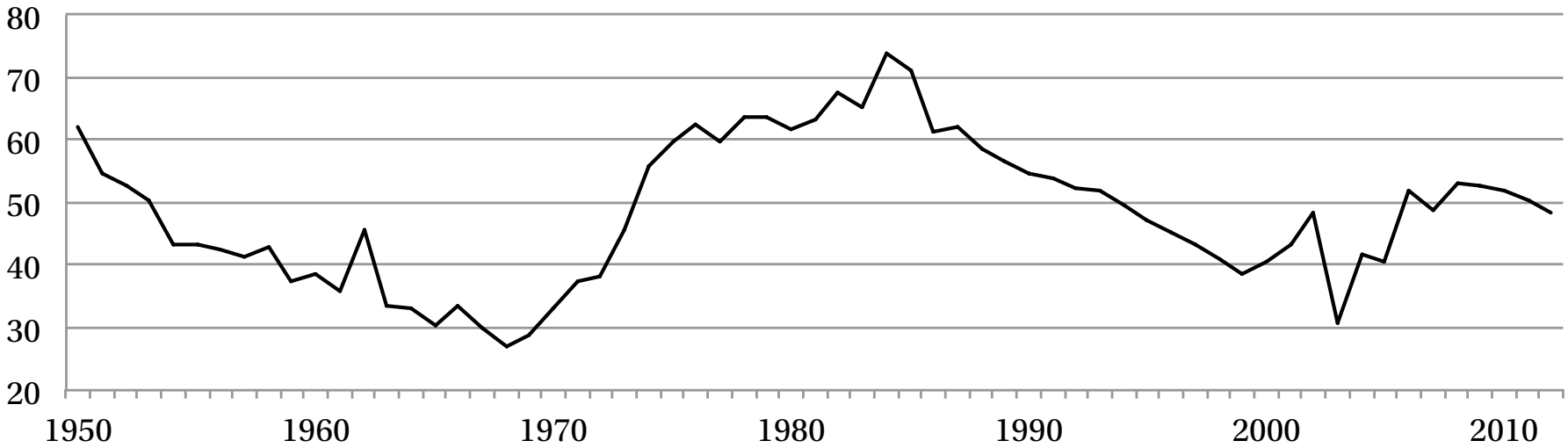
| *US* | bn\$/y | \$/kW/y | \$/MWh |
|---|---|---|---|
| Capital | 22.7 | 227 | 33.4 |
| O&M | 15.1 | 151 | 22.2 |
| Fuel | 5.5 | 55 | 8.1 |
| Back-end | 0.9 | 9 | 1.4 |
| Development | | | 9.5 |
| Total | 44 | 443 | **75** |

| *US* | |
|---|---|
| €/kW/y | €/MWh |
| 198 | 29.0 |
| 131 | 19.3 |
| 48 | 7.1 |
| 8 | 1.2 |
| | 8.3 |
| 385 | **65** |

| *FR* | |
|---|---|
| €/kW/y | €/MWh |
| 89 | 13.4 |
| 188 | 28.5 |
| 48 | 7.3 |
| 13 | 1.9 |
| | 7.7 |
| 338 | **59** |

# Comparisons: Nuclear vs. Coal

- No carbon pricing
- Coal: dominant baseload technology
- McNerney et al. (2011): stable 52 $/MWh over 1968–2010




- Consensus: coal levelized cost is scheduled to stay put
- US: nuclear 44% dearer than coal, bound to increase
- France: less clear cur conclusion, nuclear cheaper, coal dearer
- Clean energy drive: cost of carbon capture

# Comparisons: Nuclear vs. Natural Gas & Wind

- Natural Gas: major new fuel but not baseload
- Median case: $50 + 14 = 64$ \$/MWh, cheaper than nuclear
- Wind: low carbon content (Life Cycle Analysis)
- Capacity Factor (resource quality): 27.5% in US vs. 21.3% in EU
- Levelized cost: 76\$/MWh in US, 78 €/MWh in Europe
- Nuclear power likely more expensive than wind power in Europe
- Wind advantage clearer in US