Le Coût de l'Électricité Thermonucléaire en France à la suite de la catastrophe de Fukushima

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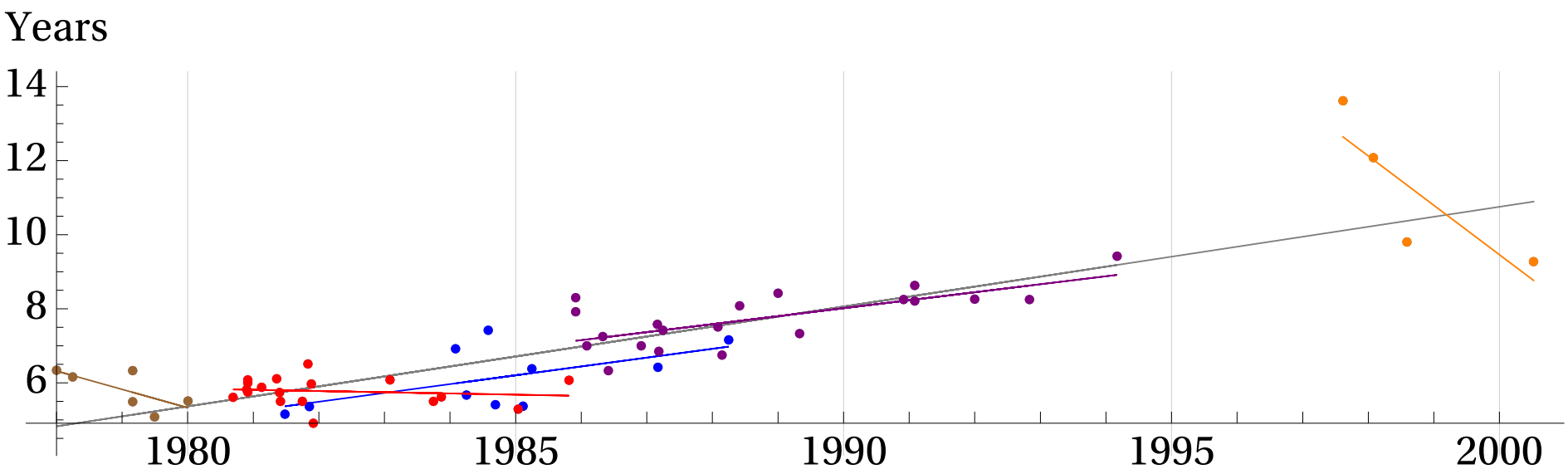
French Second Generation Nuclear Reactors

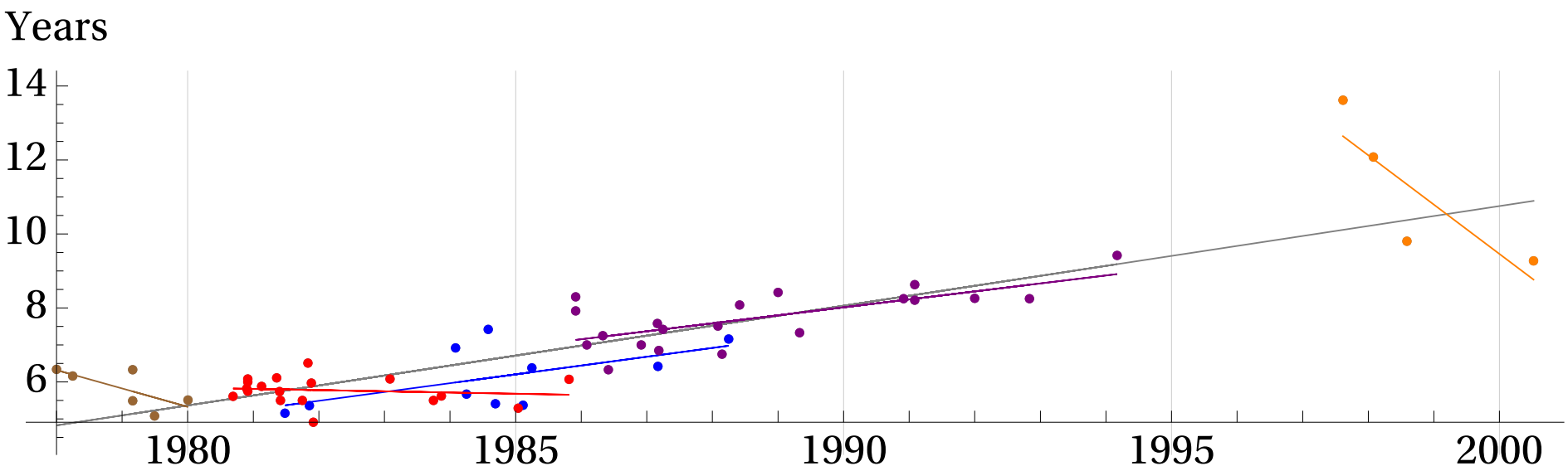
- Construction duration of 58 French nuclear reactors
- Function of the date of commercial operation
- Distinct colors and linear fittings for the five batches
- Source: PRIS database, International Atomic Energy Agency



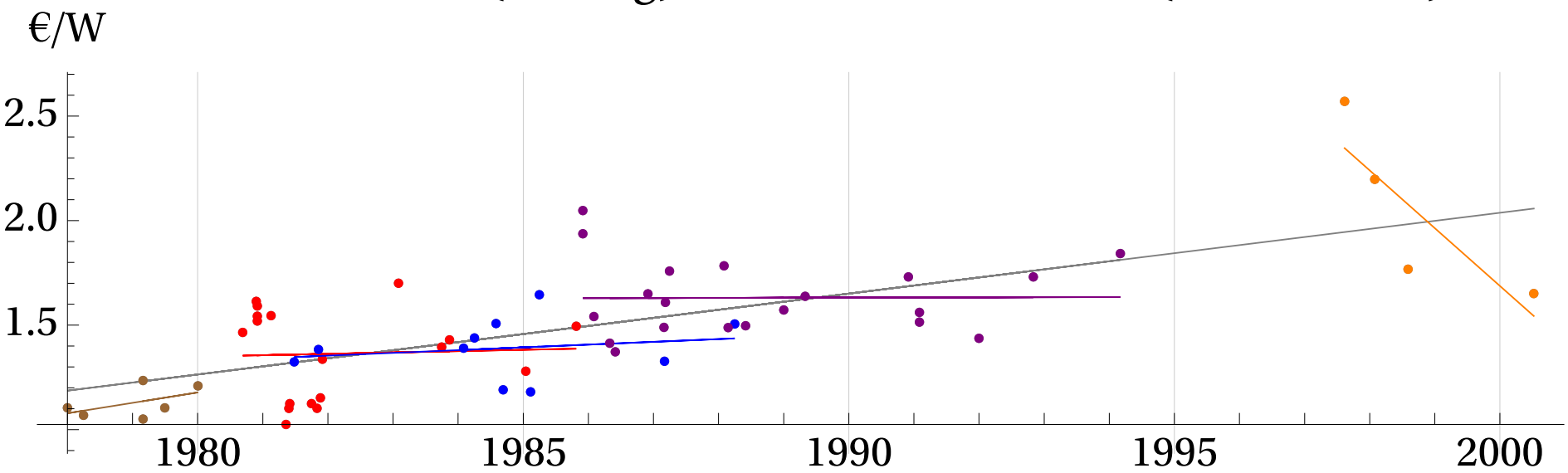
Evolution of Plant Cost for Second Gen. Reactors

- 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

Capacity Factor in the French Mix

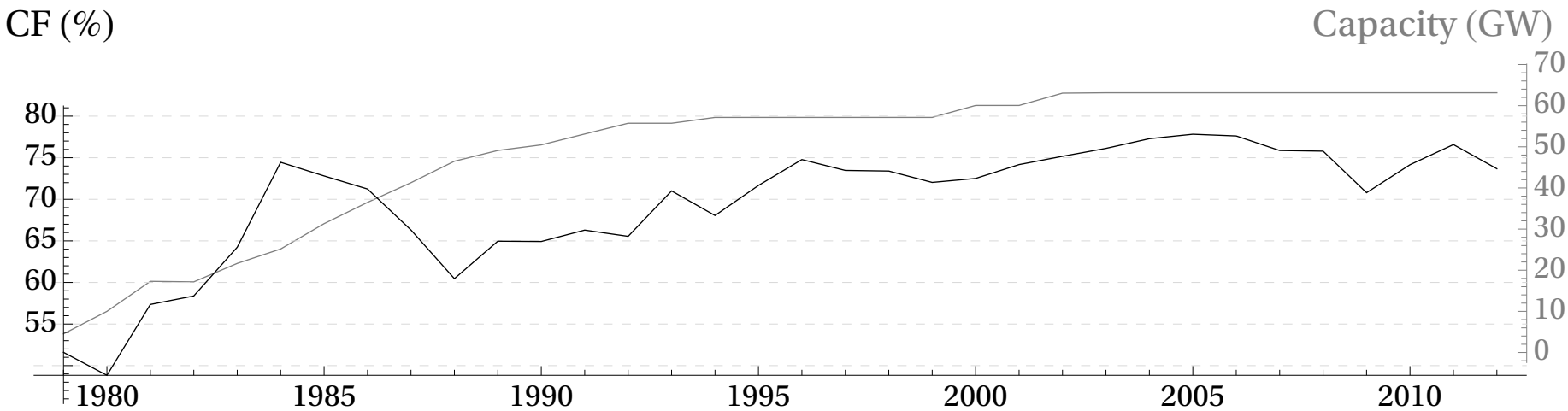
- Capacity Factor: ratio of actual output to theoretical maximum

Country	France			Germany		
Fuel (2013)	**GW**	**Twh**	**CF**	**GW**	**TWh**	**CF**
Nuclear	63	404	73%	12.1	92	87%
Lignite				24.9	145	67%
Coal	6	19.8	38%	30.2	110	42%
Natural Gas	10	19.5	22%	23.9	39.4	19%
Hydro	25	75.7	35%	10.8	24.4	26%
Wind	8	15.9	23%	32.5	47.2	17%
Solar	4	4.6	13%	35.7	29.7	10%
Biomass				5.4	35.9	76%

French Data: RTE German data: Fraunhofer, Federal Network Agency

Availability & Capacity Factor of French Nuclear Fleet

- 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 ?

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

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 given 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

- Coal: dominant baseload technology (no carbon price)
- Levelized cost stable at 52 \$/MWh, likely to remain so
- 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

Transition towards a Sustainable Electrical system

- All transitions take decades, some propositions:
- $\nearrow$ Energy savings, $\searrow$ electric heating, $\nearrow$ CHP
- Slow phasing out of current nuclear (conserve economic value)
- Replace $\frac{1}{2}$ to $\frac{2}{3}$ with EPRs, breeders, modular reactors
- Mediterranean Offshore Wind
- Maghreb partnership for fossil fuels and solar
- Mandatory DSM for big clients, public buildings
- Pumped storage: adapt all current hydro, develop small units
- Biomass: cover France back with forest (labor intensive)
- Fund local initiative with 50% co-funding
- Fund research and prototypes not expansion of mature technologies