16TH IAEE EUROPEAN CONFERENCE | LJUBLJANA

Cost Estimates and Economics of Nuclear Power Plant New Build: Literature Review and Modelling Analysis

27 August 2019

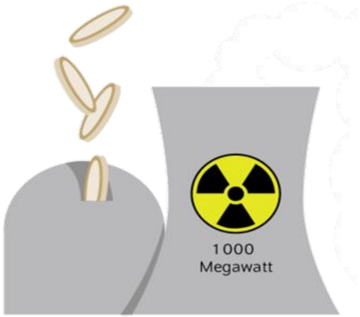

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Photo: EDF


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AGENDA

1. Introduction
2. Historical Construction Costs of Nuclear Reactors in the U.S. and France
3. Current Costs of New Build Reactors in Europe and the U.S.
4. Profitability of New Nuclear Reactors
5. Future Perspectives of Nuclear Power

Nuclear Power: “too cheap to meter” (Lewis L. Strauss, 1954)

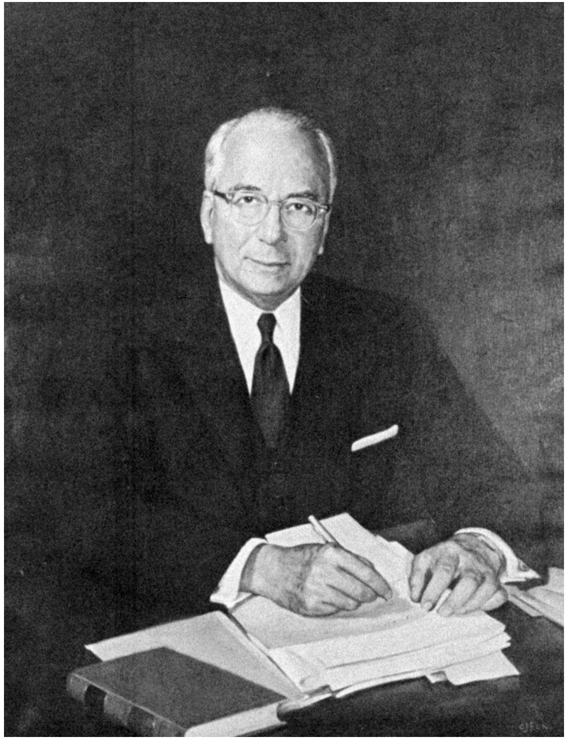
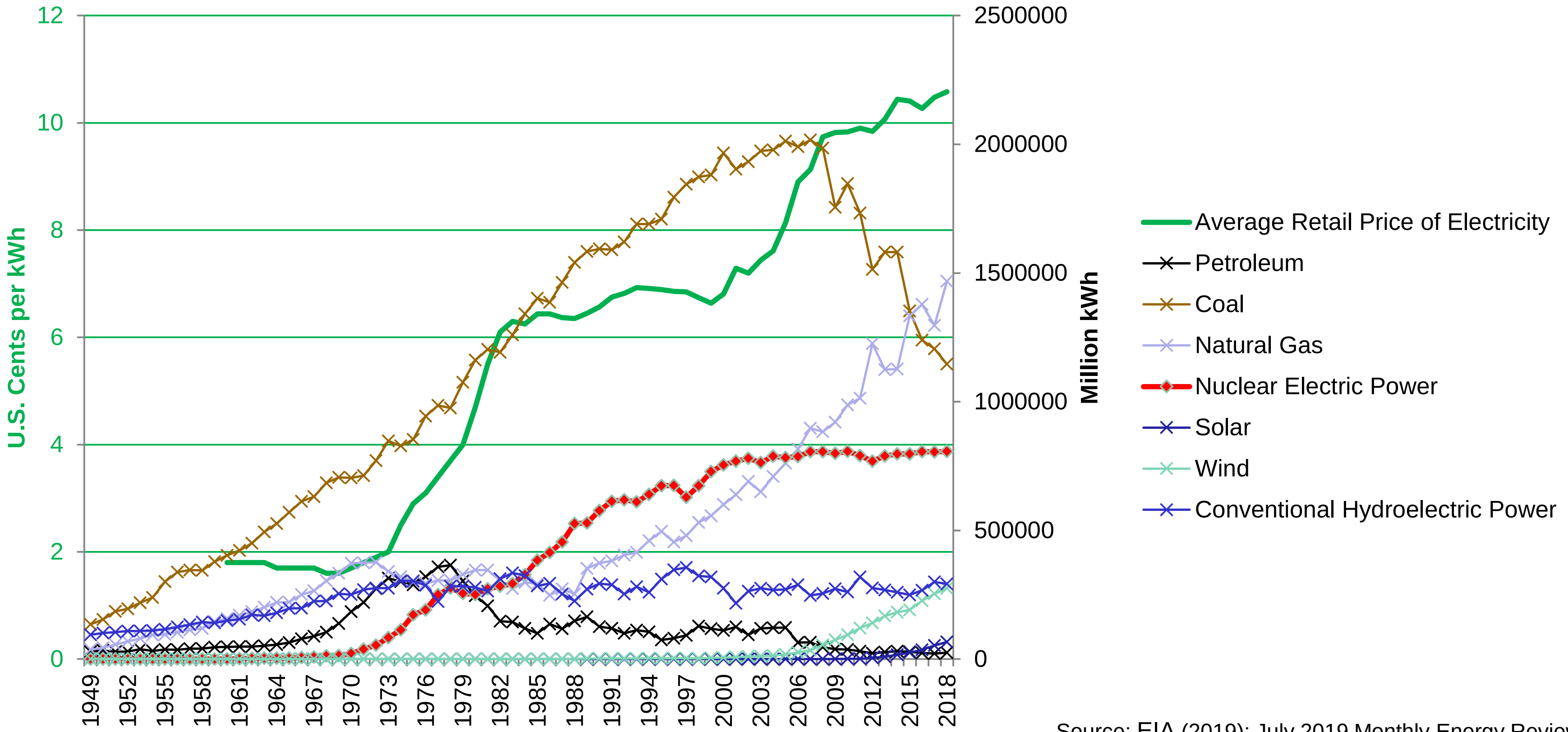


Photo: National Oceanic and Atmospheric Administration/Department of Commerce

“It is not too much to expect that our children will enjoy in their homes electrical energy too cheap to meter […], will travel effortlessly over the seas and under them and through the air with a minimum of danger and at great speeds. […] This is the forecast for an age of peace.”

Lewis L. Strauss, Chairman U.S. Atomic Energy Commission, @ The Founders' Day Dinner, National Association of Science Writers,
16 September 1954

Nuclear Power: … is, however, still measurable



Source: EIA (2019): July 2019 Monthly Energy Review

Nuclear Power: Different Cost Levels

	Cost Level
	Owner‘s Cost
+	Engineering, Procurement, and Construction Costs (EPC)
+	Contingency Provision
=	**Overnight Construction Costs (OCC)**
+	Interest during Construction (IDC) (Time-Related Costs)
=	**Total Construction Costs** (Total Investment)

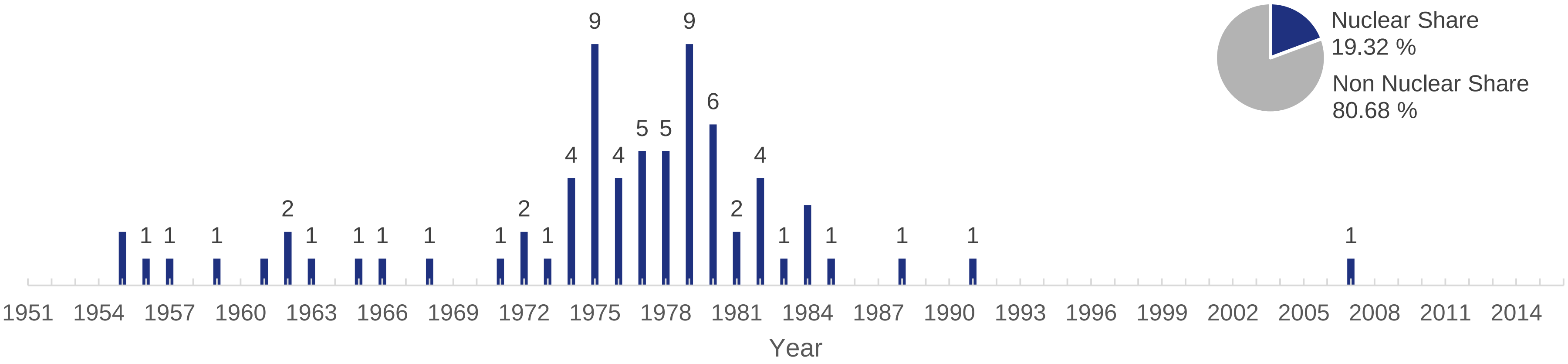
Source: Own depiction based on D’Haeseleer (2013).

2. Historical Construction Costs of Nuclear Reactors in the U.S. and France

USA: Decentralized, Heterogeneous, Regulatory Instability of the Nuclear Sector

Reactor Construction Starts in the U.S.

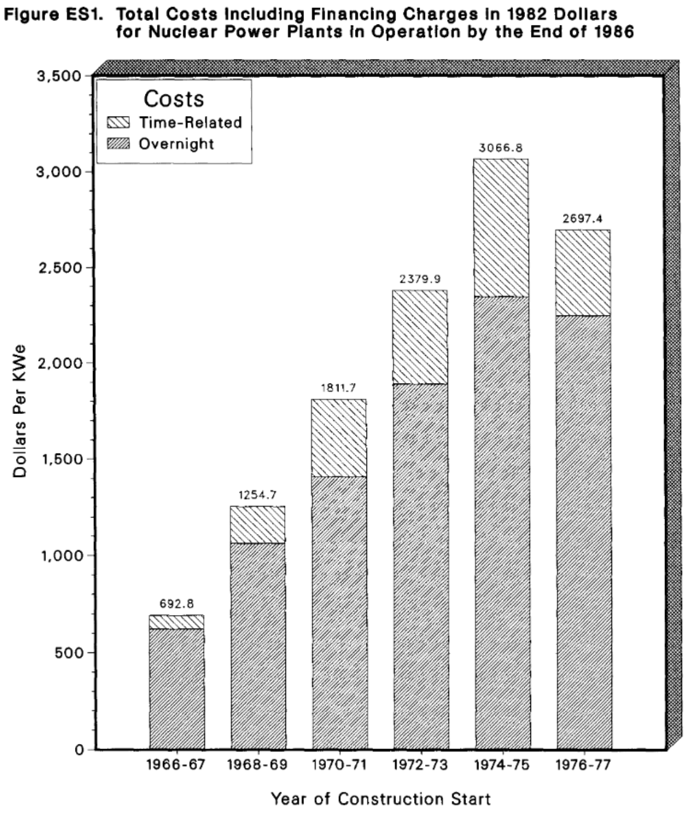
Electricity Production Share 2018



Source: Own depiction based on IAEA PRIS

- 1974: 54 operating reactors; 197 ordered
- Less than half of the 197 ordered were actually build
- 1979: Partial core meltdown in Three Mile Island plant fuelled public concerns about safety
- Institutional changes, new regulations and safety requirements raised hurdles of investments in new nuclear reactors
- OCC increased about 7 times from the first to the latest reactor

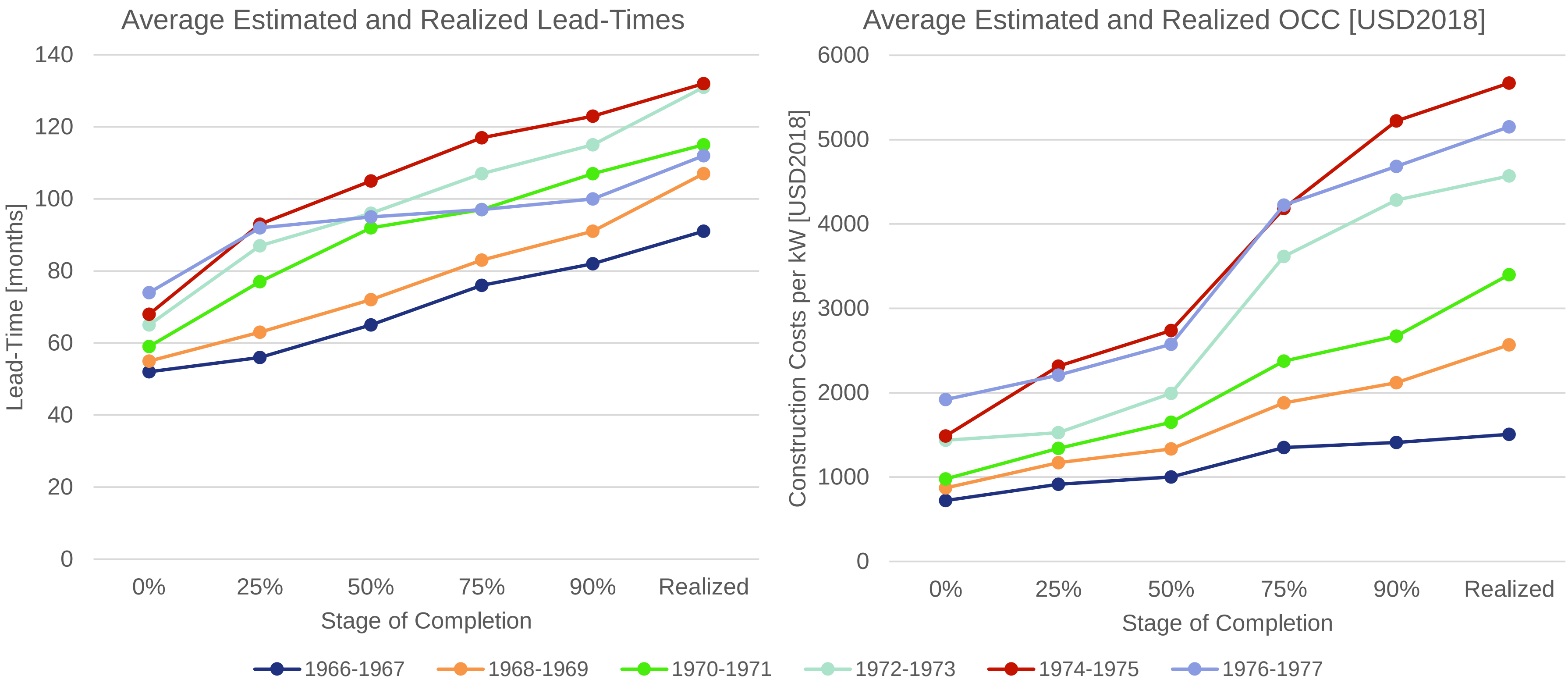
Cost Increases during Nuclear Boom in the U.S. (1966-1977)



Source: DOE/EIA (1986): Analysis of nuclear power plant construction costs

- OCC make approx. 75% of total costs
- Potential economies of scale were offset by increase of construction time
- Drivers for costs and lead-times:
  - Internal: technological complexity, management structure, productivity, etc.
  - External: interest rates, regulatory changes, safety requirements, etc.

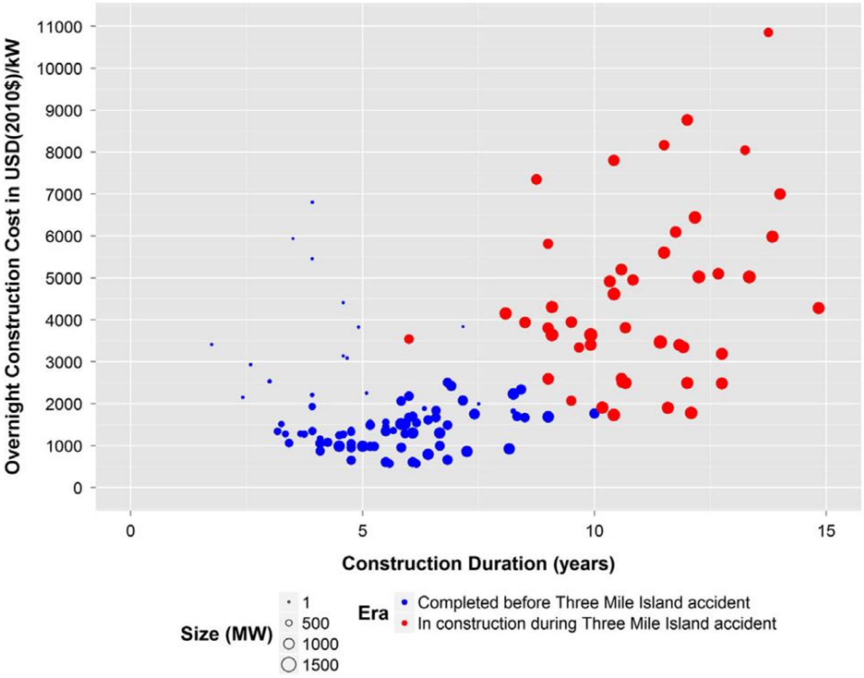
Underestimates of Lead-times and OCC in the U.S. (1966-1977)



Number of reactors	11	26	12	7	14	5

Source: Own depiction, data derived from DOE/EIA (1986)

Escalation of OCC in the U.S. after Three Mile Island Accident (1979)



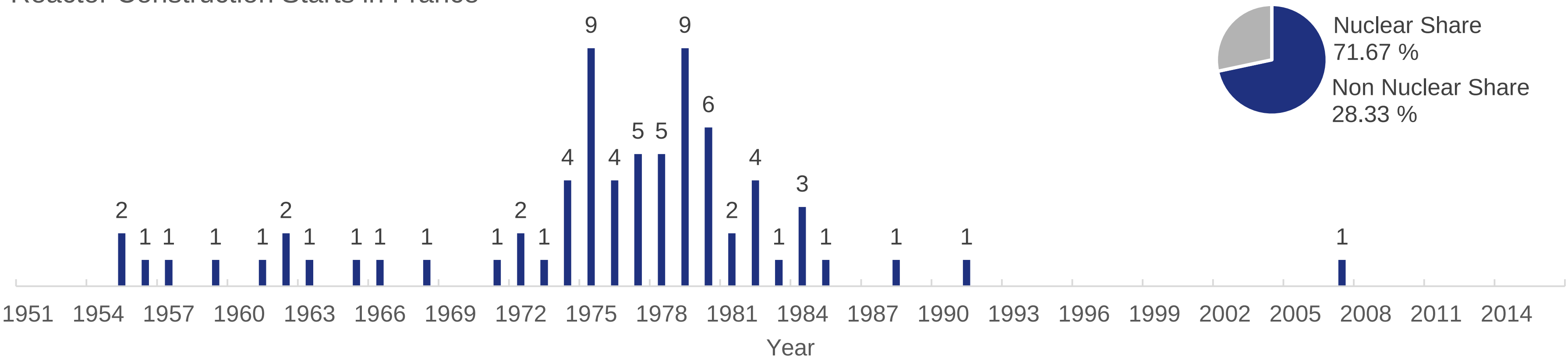
Note: Koomey et al. (2017) found that OCC by Lovering et al. (2016) as presented here exclude IDC and therefore cost escalations occurred due to increase in lead-time. Of a data set of 180 reactor, the average cost overrun is 117.3% and average time overrun is 64% (Savacool et al. (2014)). The use of OCC in this context is nevertheless legitimate as long as the figures are not compared to total construction costs. The latter incorporate IDC. OCC attempt to show the construction costs without the bias of interest rates and lead-time.

Source: Lovering et al. (2016)

France: Standardized, Centralized and Regulatory Stability Suggest “Best Conditions” (Escobar / Lévêque, 2012) for Nuclear Power

Reactor Construction Starts in France

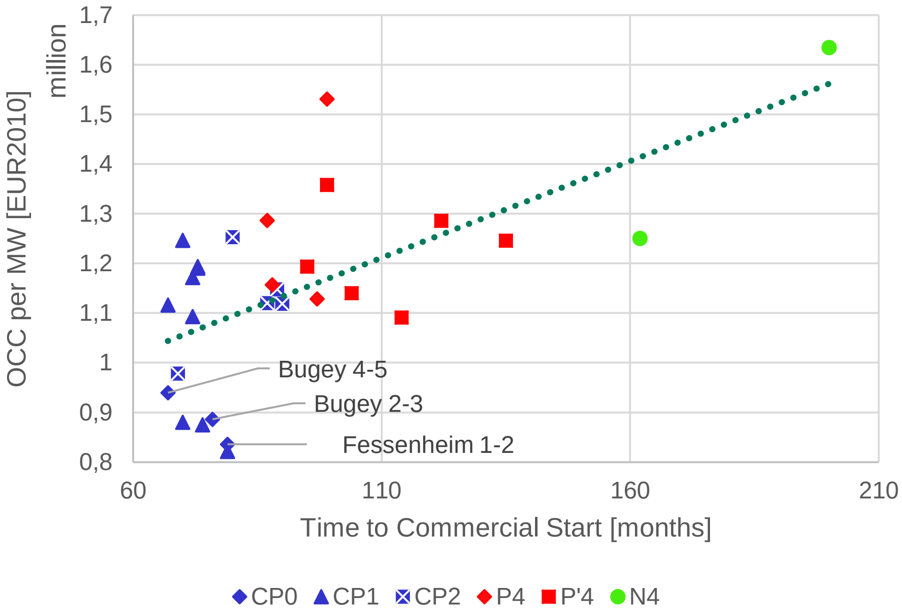
Electricity Production Share 2018



- Widespread use of nuclear energy: approx. ¾ of the electricity in France
- “Best conditions”: centralized decision making, high degree of standardization and regulatory stability
- OCC increased by a factor of 1.5 (Escobar / Lévêque, 2012) to 3.5 (Grubler, 2010) from the first to the latest reactor
- French “best conditions” still suggest inherent costs escalations of nuclear power

The French-Case: "Gradual Erosion of EDF Determination to Standardize" (Grubler, 2010)

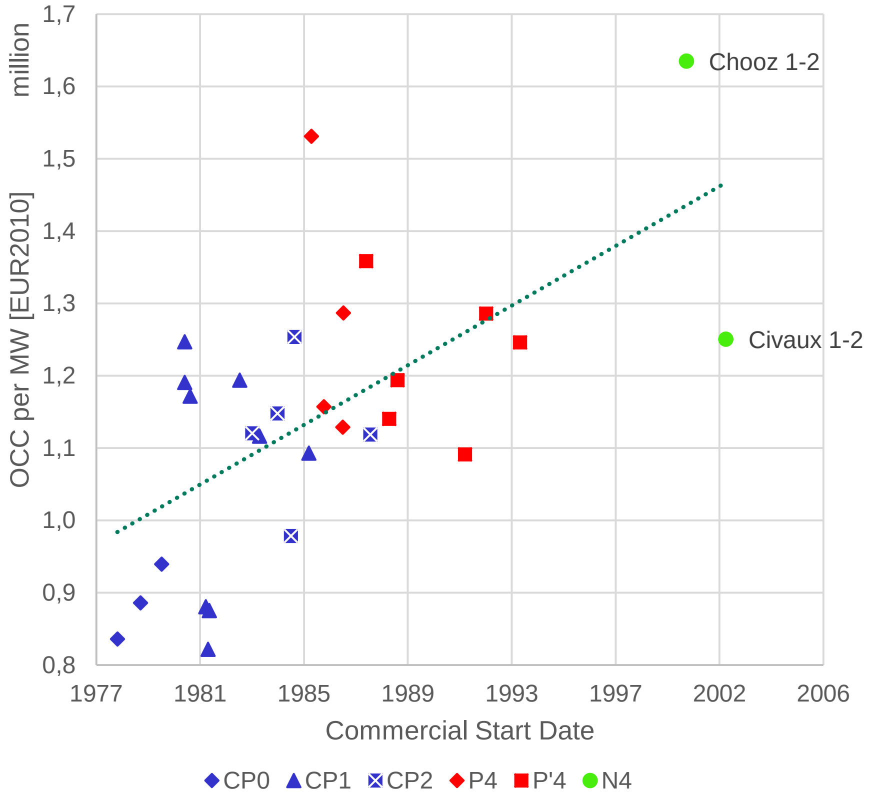
Order series	Reactor type	Number built	Mean Construction Time [months]
CP0	PWR 900 MW Westinghouse license	6	63
CP1	PWR 900 MW Westinghouse license	18	65
CP2	PWR 900 MW Westinghouse license	10	67
P4	PWR 1,300 MW Westinghouse license	8	78
P'4	P4 "frenchified" Westinghouse	12	90
N4	PWR 1500 MW New French design	4	126
EPR	EPR 1600 MW Framatome-Siemens	1	n.a.

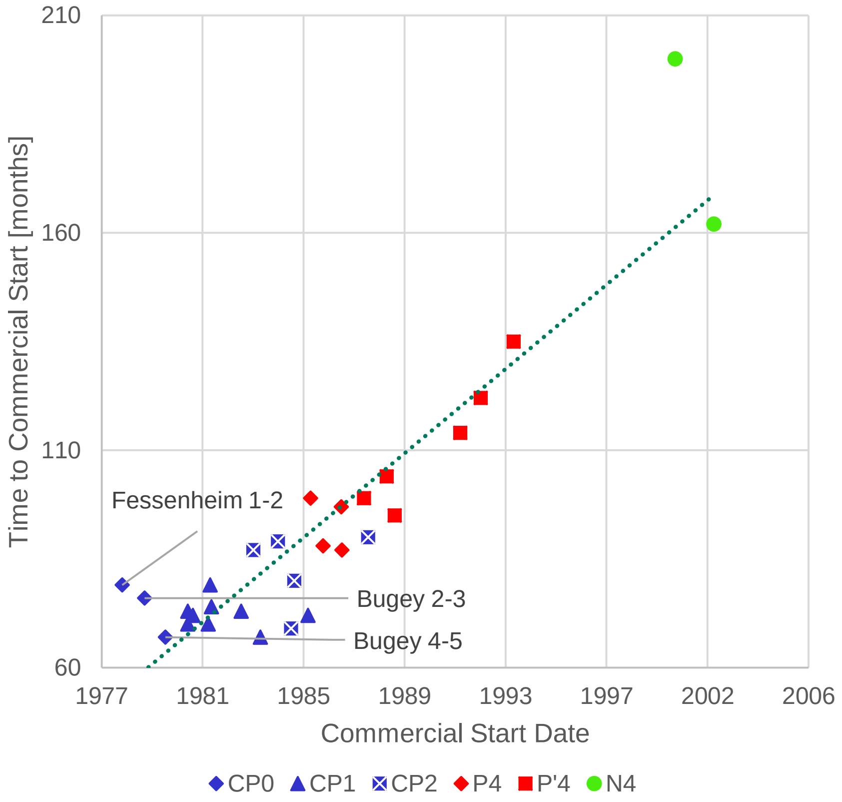


Source: Own depiction, data derived from Cour de Comptes (2012).

Note: Koomey et al. (2017) express considerable criticism about the data published by CdC (2012). Koomey et al. calculate total OCC of the 58 currently operative units to about €83 billion instead of €73 billion from CdC. These higher costs origin in the inclusion of additional construction-related engineering and labour costs and pre-operating charges. Further, IDC published by French utility EDF amount some €23 billion in contrast to CdC's €13 billion. Summing up IDC and actual OCC presented by Koomey et al. total construction cost amount €106 billion.

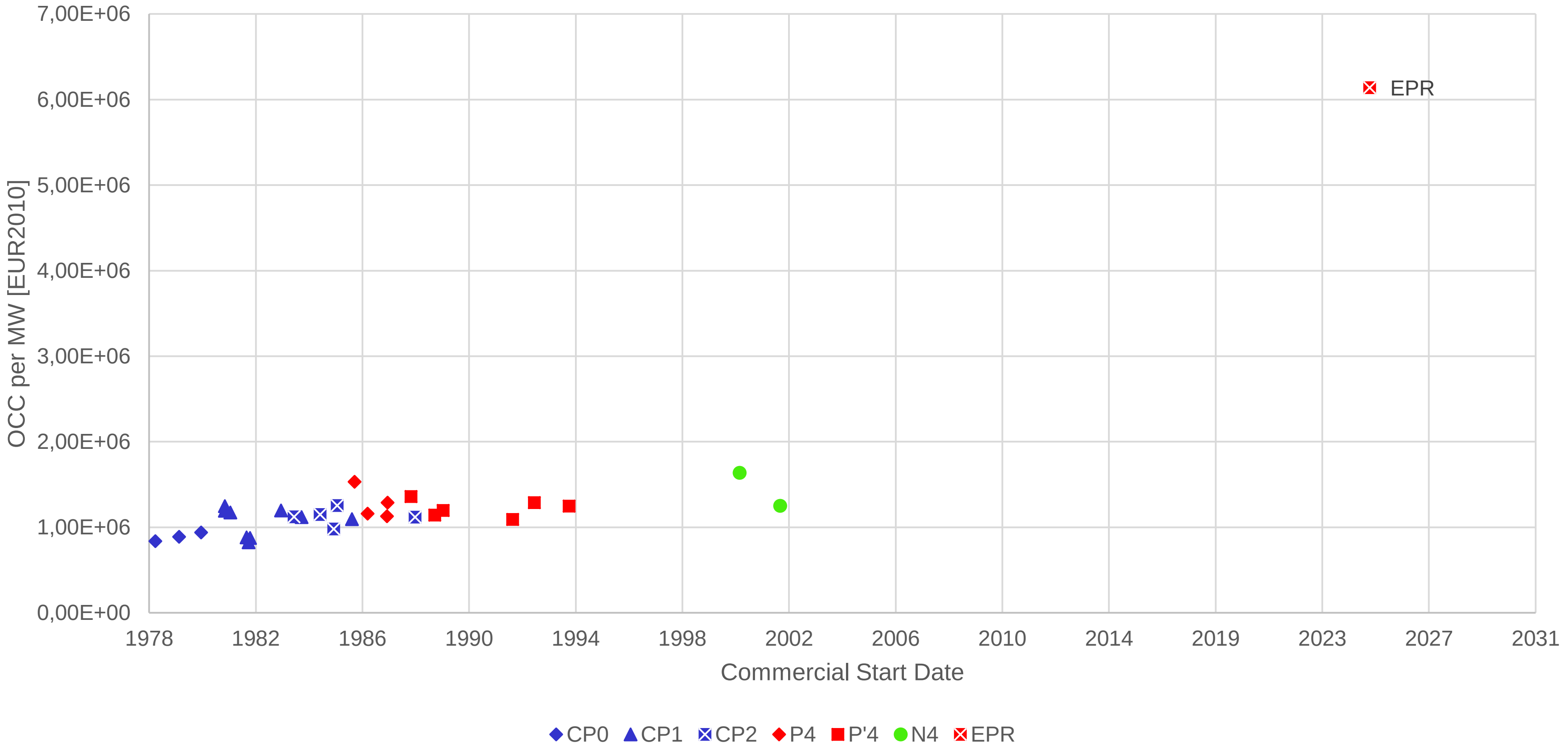
Increasing OCC with Increasing Lead-times and Technology Evolution



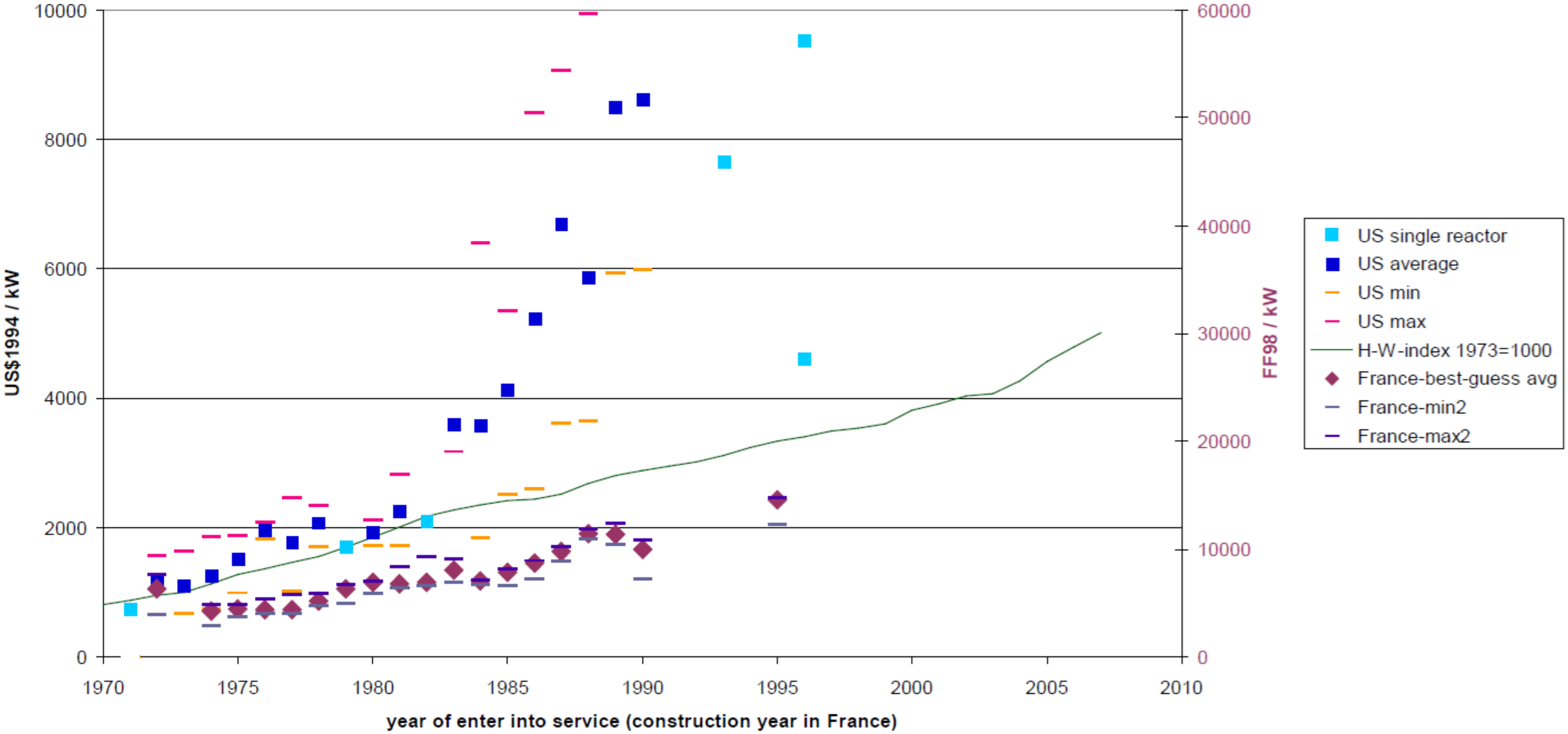


Source: Own depiction, data derived from Cour de Comptes (2012).

Construction Costs for EPR (1,600 MW) per MW: EUR_{2018} 6,810



Increases in Construction Costs are Inherent; However, Centralized, Standardizes System Reveals Less Cost Escalation



Source: Grubler (2009).

Interim Conclusion 1

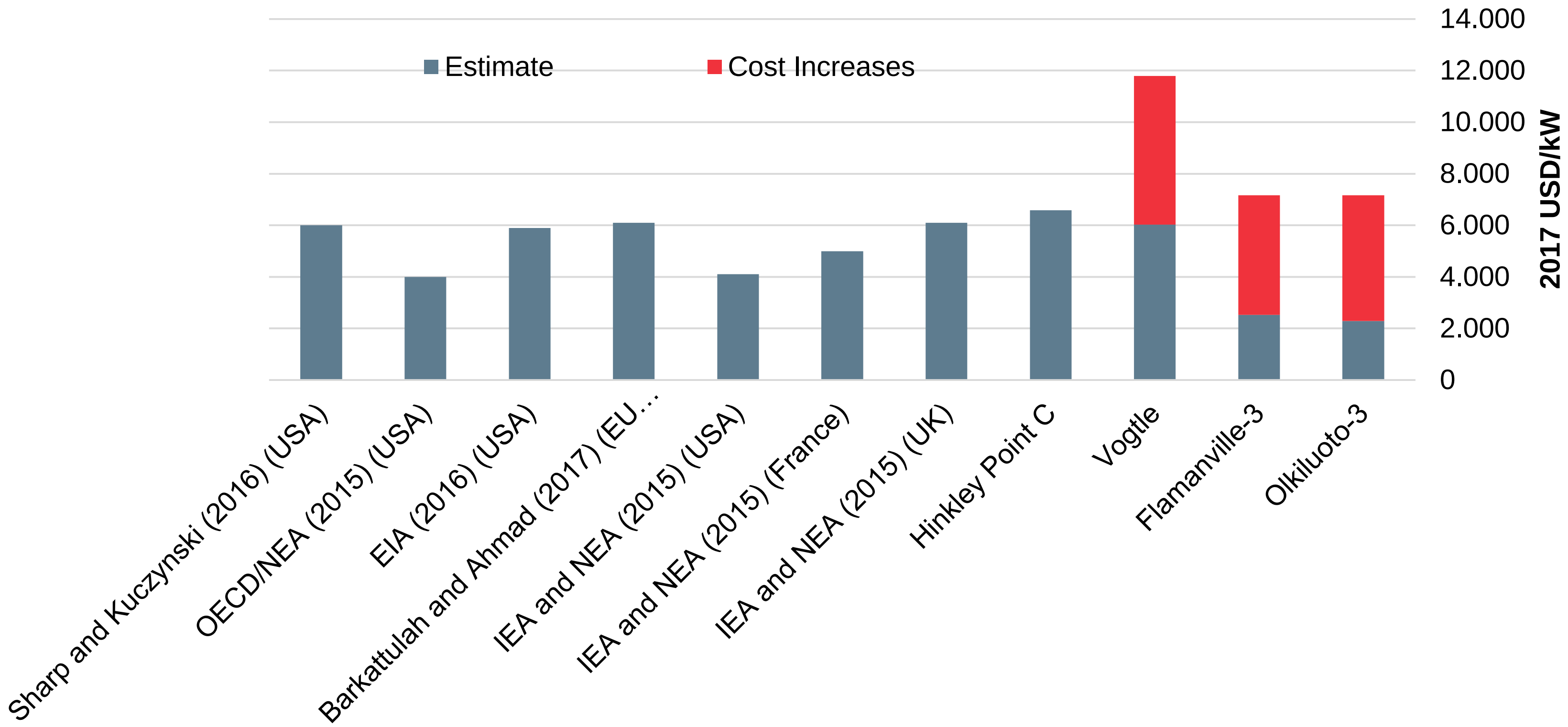
1. **If any, low economies of scale**

2. **Bigger in NOT better:** Bigger capacities lead to higher complexity—which translates into higher OCC—and longer lead-times—which translates into higher time-related costs—and therefore higher total construction costs

3. **Standardized and centralized organization results in lower cost escalation rates**

3. Current Costs of New Build Reactors in Europe and the U.S.

Current OCC Estimates of Gen III / III+ Nuclear Reactors in the USA and Europe and Cost Increases for Ongoing New Build Projects



Interim Conclusion 2

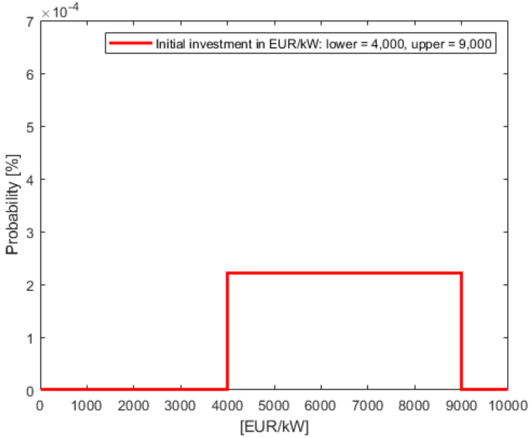
“Seventy years later the industry is still trying to demonstrate how this [nuclear reactor technology] can be scaled up cheaply enough to compete with coal and natural gas [and wind].”
(Davis 2012)

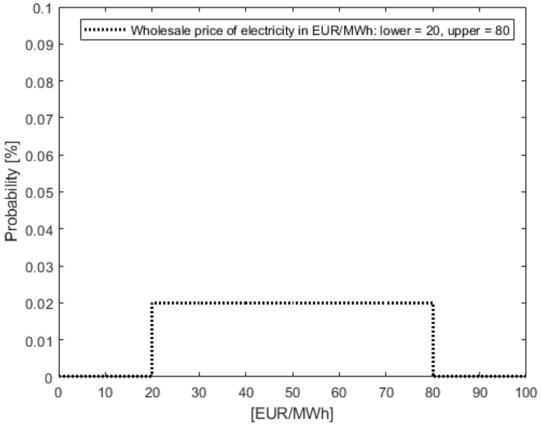
4. Profitability of New Nuclear Reactors

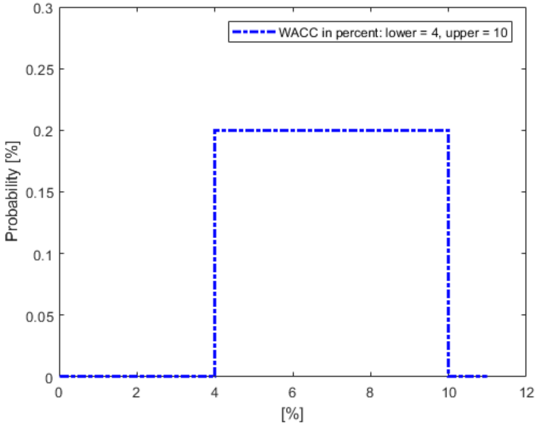
Nuclear Power: Profitability under scrutiny – Monte Carlo Simulation

- **Simple and established technique to include uncertainty in quantitative models**
- **Calculation of Net Present Value (NPV) with parameter variations (uniform distribution)**
  - Initial investment (OCC)
  - Wholesale price of electricity
  - Weighted average cost of capital (WACC)

$$NPV(i,N) = \sum_{t=0}^{N} \frac{R_t}{(1+i)^t}$$







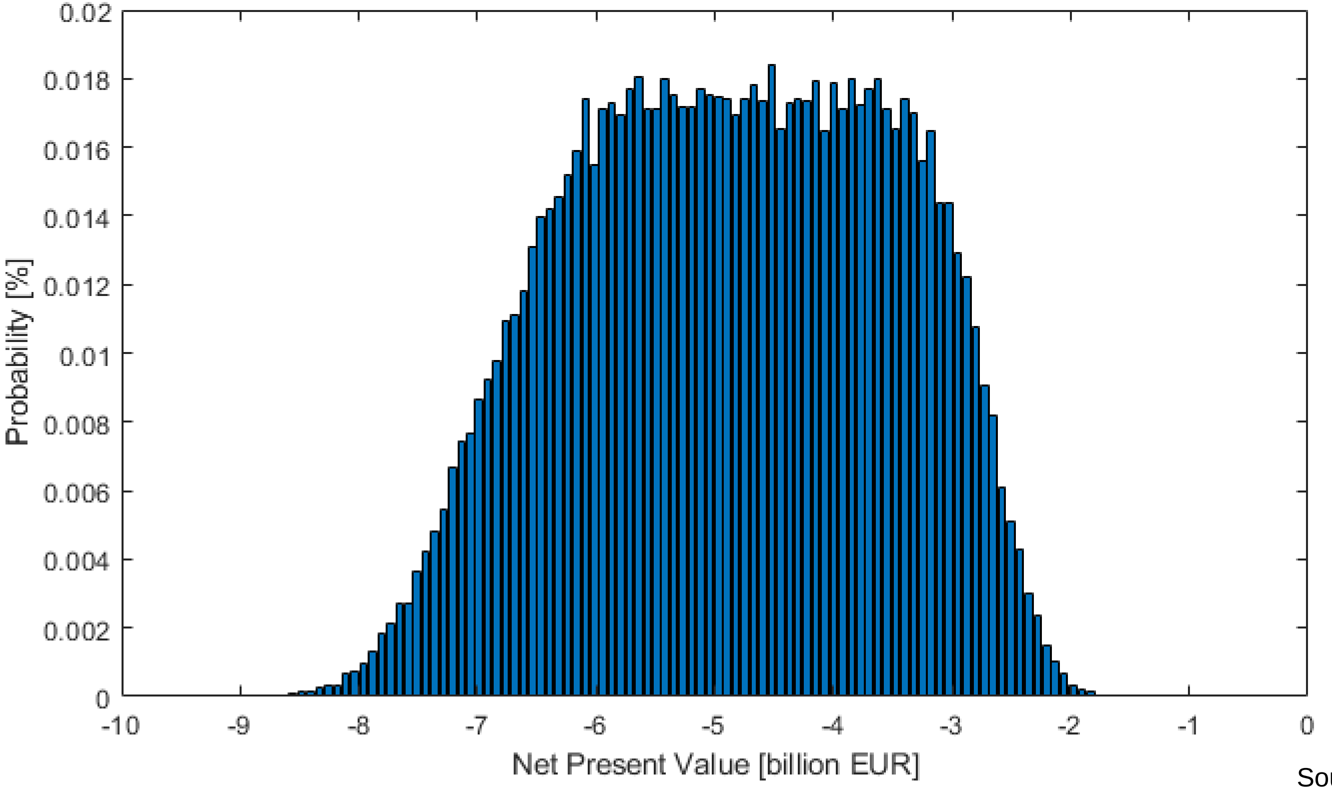
Source: Own calculation

Nuclear Power: Profitability under scrutiny – Monte Carlo Simulation

Inputs	Distribution	Range
Initial investment (OCC)	Uniform	4,000-9,000 EUR/kW
Wholesale price of electricity	Uniform	20-80 EUR/kW
Weighted average cost of capital (WACC)	Uniform	4-10 %
Plant capacity to grid	Constant	1,000 MW_{el}
Plant lifetime	Constant	40 years
Construction time	Constant	5 years
Maintainance costs	Constant	90 EUR/kW
Operation and fuel costs	Constant	12 EUR/MWh

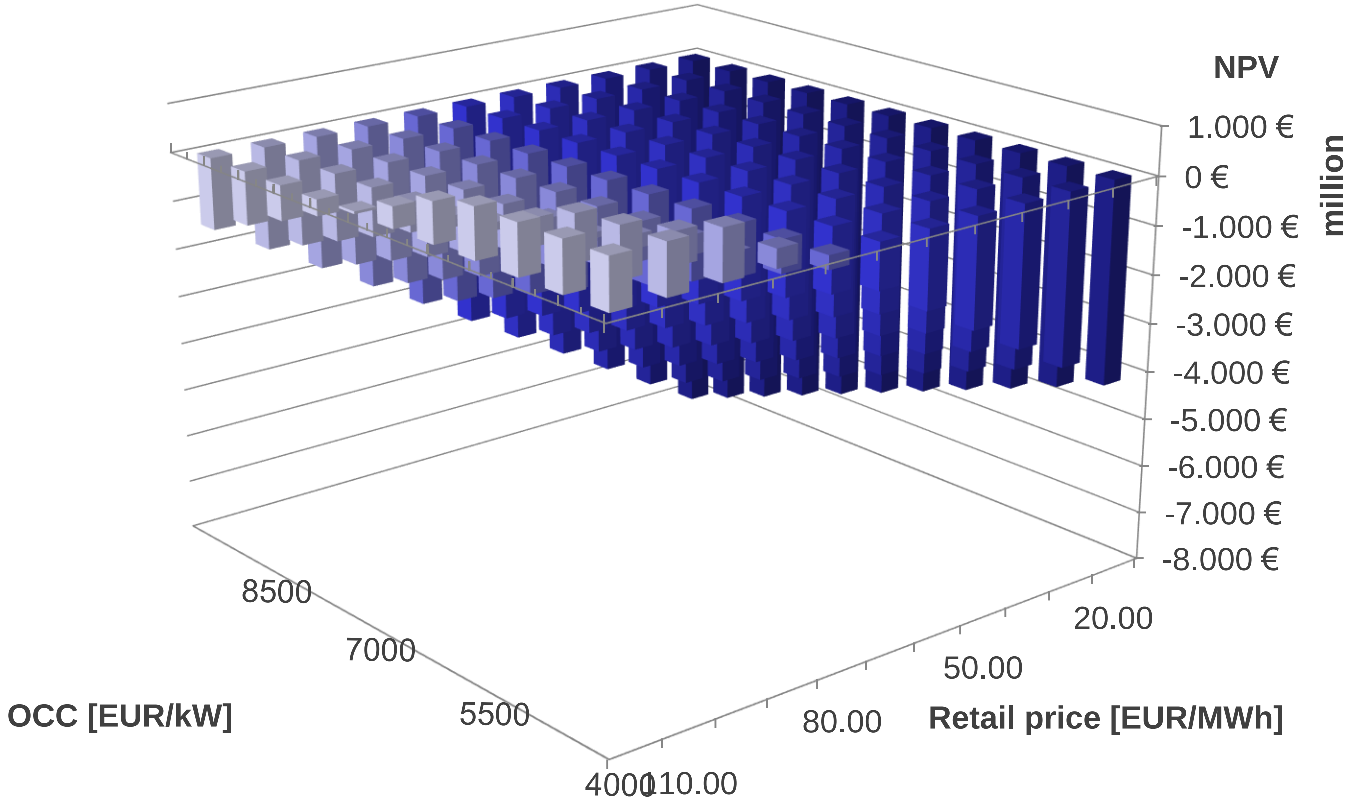
Source: Own calculation

Investment in Nuclear Power: Average loss of EUR 4.8 billion



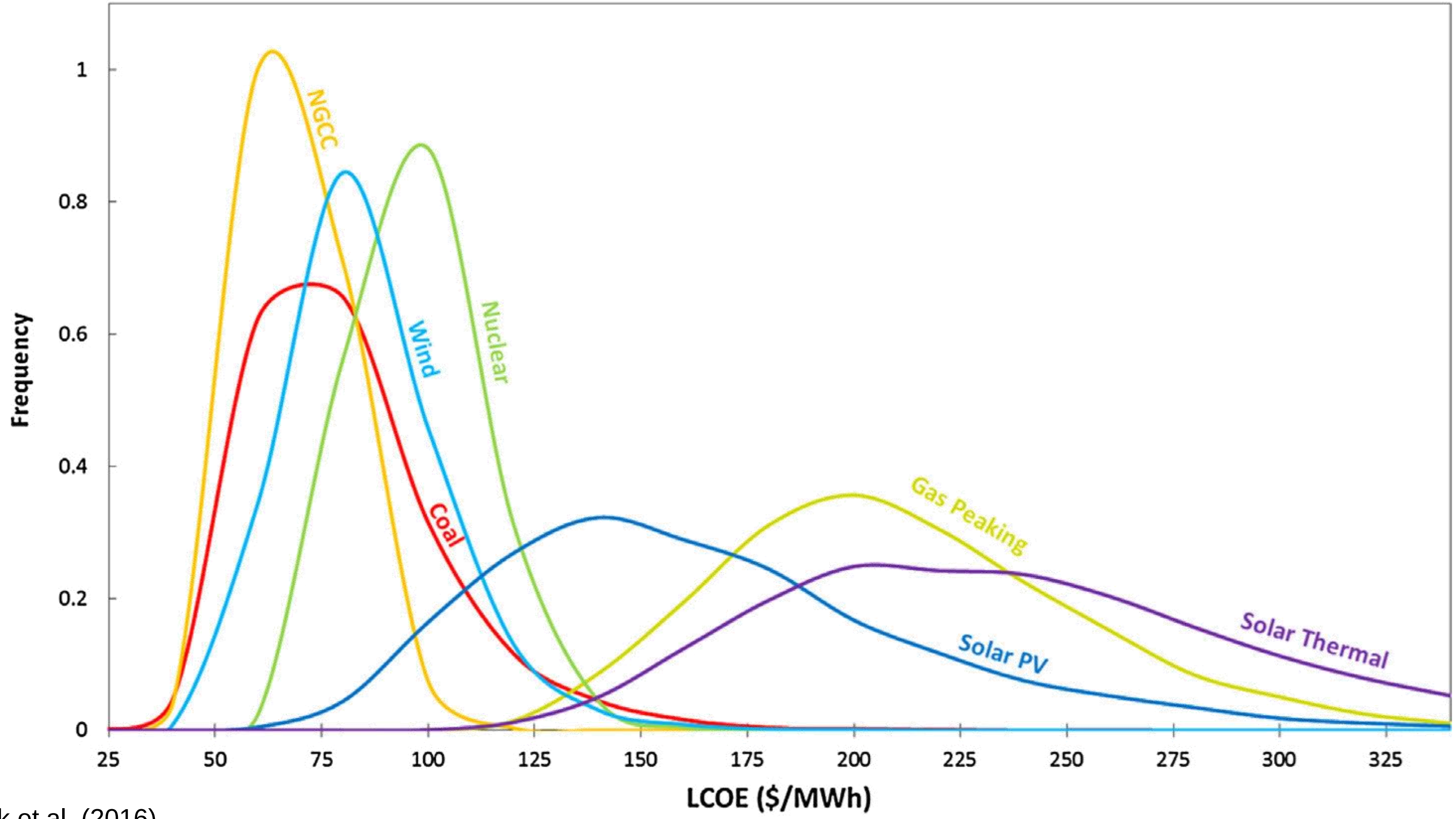
Source: Own calculation

Levelized Cost of Electricity (LCOE) at best EUR 90 / MWh



Source: own calculation.

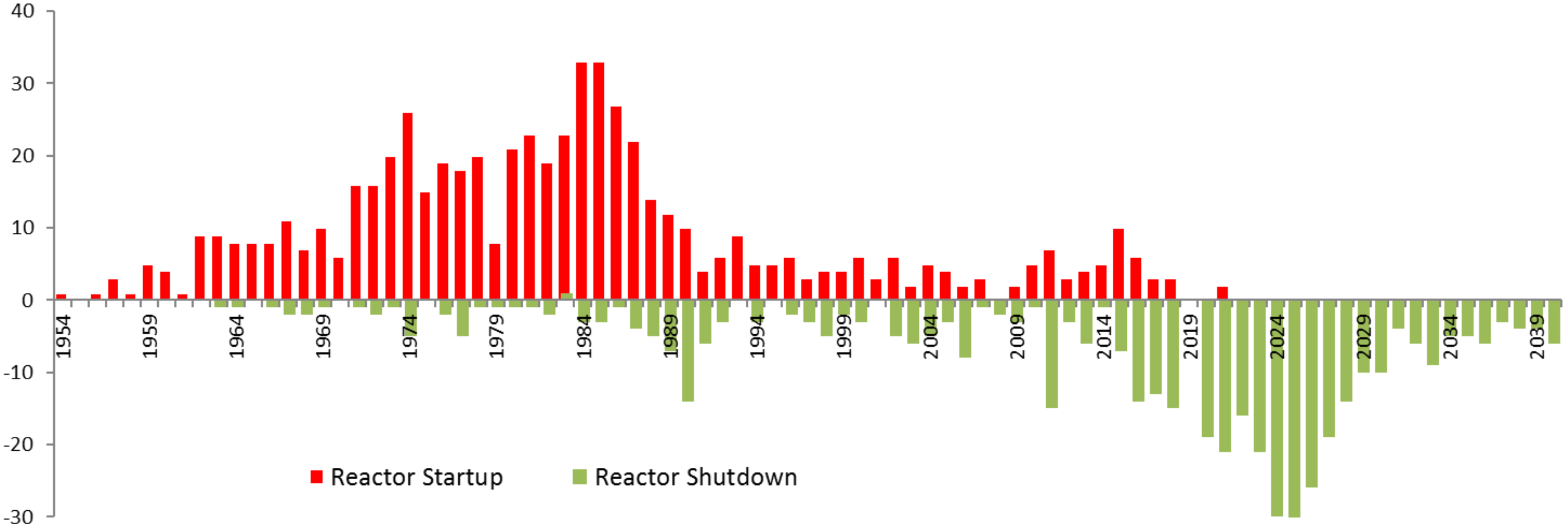
Heck et al. (2016) Monte Carlo Simulation of LCOE: Nuclear Power Less Likely to be Competitive with Wind



Source: Heck et al. (2016).

5. Future Perspectives of Nuclear Power

Nuclear Plant Decommissioning Outpacing New-Build



Source: Own depiction, based on IAEA (2017) PRIS Database

Small Modular Reactors (SMR):

"Advanced SMRs range in size up to 300 megawatts electrical (MWe), employ modular construction techniques, ship major components from factory fabrication locations to the plant site by rail or truck, and include designs that simplify plant site activities required for plant assembly." – U.S. Department of Energy

Source: NuScale Power, LLC, All Rights Reserved

No short-/mid-term prospects for SMRs

- The concept of SMRs has been around since the dawn of the nuclear age.
- No SMR has ever been operated and current projects (if not abandoned) suffer from serious delays – both in construction and reactor design.
- Benefits of mass production are very optimistic due to the relatively small number of very costly parts.
- Harmonized regulatory framework and licensing on a broad basis is not in sight. Neither is the supply chain.
- In sum, economic viability of SMRs is not clear. Potential benefits of design and mass production must be weighed against technical and security risks as well as potentially higher O&M costs, fuel consumption and waste according to design (e.g. iPWRs).
- SMRs can increase proliferation risk due to increased flow of fissile material.

The perspectives of nuclear power deployment depend in the long term on…

… the development of costs in relation to other low-carbon options, and the economics of investments into new capacities.

While there is a consensus in the literature that nuclear power is not competitive under regular market economy, competitive conditions, <u>at least two issues</u> need to be considered going forward:

- First, the treatment of costs in other, non-market institutional contexts:
  a) Indigenous supplies or "home suppliers" (Thomas, 2010)
  b) Subsidized export models of countries e.g. China (Thomas, 2017) or Russia (Hirschhausen, 2017).

- Second, the evolution of future technology (e.g. Gen III/III+, Gen IV, SMR)

Final Conclusion

1. Nuclear power historically struggled with ever increasing costs. To this day, technological improvements and potential learning effects did not materialize in cost reductions.
2. The literature and own calculations suggest that investments in new nuclear reactors in Europe and the U.S. are involving heavy losses for a private investor under current market conditions.
3. The economic benefits of Small Modular Reactors (SMRs) are questionable. Regulatory and technical issues pose serious challenges to the deploy of such reactors.
4. Nuclear advocates frame nuclear energy as “clean” or “renewable energy” and call for governmental support mechanisms (e.g. U.S. Zero-Emissions Credit (ZEC)), price guarantees (e.g. UK Hinkley Point C), high carbon pricing, tax cuts for nuclear power production (e.g. in Sweden), etc.). It is highly questionable whether those should be granted owing to the rather uneconomic nature of nuclear power and the associated risks for the national budget—and not inconsiderable threats to humankind and environment.

July 2019: DIW Weekly Report 30/2019

DIW Weekly Report 30 2019

AT A GLANCE

High-priced and dangerous: nuclear power is not an option for the climate-friendly energy mix

By Ben Wealer, Simon Bauer, Leonard Göke, Christian von Hirschhausen, and Claudia Kemfert

- Analysis of the historical, current, and future profitability of nuclear power plants
- Consideration in terms of economic history and financial examination of net present values of investments in nuclear power
- Private economy investment was unprofitable in the past, and this also applies to new investment
- Due to danger of radioactive emissions and proliferation, nuclear energy technology is high-risk
- Policy makers should reject nuclear energy as an option for sustainably supplying energy

Investing in a nuclear power plant is uneconomical. This holds for all plausible ranges of specific investment costs, weighted average cost of capital, and wholesale electricity prices

Source: own calculations.

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FROM THE AUTHORS

"Nuclear power was never designed for commercial electricity generation; it was aimed at nuclear weapons. That is why nuclear electricity has been and will continue to be uneconomical. Further, nuclear energy is by no means 'clean.' Its radioactivity will endanger humans and the natural world for over one million years."
— Christian von Hirschhausen, Coauthor of the present study —

MEDIA

Audio Interview with Christian von Hirschhausen (in German)
www.diw.de/mediathek

DIW Wochenbericht 30 2019

AUF EINEN BLICK

Zu teuer und gefährlich: Atomkraft ist keine Option für eine klimafreundliche Energieversorgung

Von Ben Wealer, Simon Bauer, Leonard Göke, Christian von Hirschhausen und Claudia Kemfert

- Analyse der historischen, gegenwärtigen und zukünftigen Wirtschaftlichkeit von Atomkraftwerken
- Wirtschaftshistorische Betrachtung sowie betriebswirtschaftliche Untersuchung von Nettobarwerten für Investitionen in Atomkraft
- Privatwirtschaftliche Investitionen waren in der Vergangenheit stets unrentabel; dies gilt auch für Neuinvestitionen
- Aufgrund von Strahlungs- und Proliferationsrisiken ist Atomkraft eine risikoreiche Technologie
- Die Politik sollte Atomkraft als Option für eine nachhaltige Energieversorgung verwerfen

Eine Investition in ein Atomkraftwerk ist stets privatwirtschaftlich unrentabel, egal welche plausiblen Werte für den zukünftigen Strompreis, die spezifischen Investitionen und die Kapitalkosten angenommen werden.

Quelle: Eigene Berechnungen.

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ZITAT

„Atomkraft war niemals auf die kommerzielle Stromerzeugung ausgelegt, sondern auf Atomwaffen. Atomstrom war, ist und bleibt unwirtschaftlich. Darüber hinaus ist Atomkraft mitnichten sauber, sondern aufgrund radioaktiver Strahlung für über eine Millionen Jahre gefährlich für Mensch und Natur."
— Christian von Hirschhausen, Studienautor —

MEDIATHEK

Audio-Interview mit Christian von Hirschhausen
www.diw.de/mediathek

Thank you for your attention

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Unsuccessful Estimates of OCC and Lead-time in the U.S. (1966-1977)

Table ES1. Average Estimated and Realized Overnight Costs of Nuclear Power Plants by Year of Construction Start
(1982 Dollars per Kilowatt-Electric)

Year of Construction Start	Number of Plants	Estimated Costs at Different Stages of Completion 0%	25%	50%	75%	90%	Realized Costs
1966-1967	11	298	378	414	558	583	623
1968-1969	26	361	484	552	778	877	1,062
1970-1971	12	404	554	683	982	1,105	1,407
1972-1973	7	594	631	824	1,496	1,773	1,891
1974-1975[a]	14	615	958	1,132	1,731	2,160	2,346
1976-1977[a]	5	794	914	1,065	1,748	1,937	2,132

Table ES2. Average Estimated and Realized Lead-Times of Nuclear Power Plants by Year of Construction Start
(Months)

Year of Construction Start	Estimated Lead-Times at Different Stages of Completion 0%	25%	50%	75%	90%	Realized Lead-Times
1966-1967	52	56	65	76	82	91
1968-1969	55	63	72	83	91	107
1970-1971	59	77	92	97	110	132
1972-1973	65	87	96	107	115	131
1974-1975[a]	68	93	105	117	123	132
1976-1977[a]	74	92	95	97	100	112

Source: DOE/EIA (1986): Analysis of nuclear power plant construction costs

Unsuccessful Estimates of OCC in the U.S. (1966-1977)

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Year of Construction Start	Number of Plants	Estimated Costs at Different Stages of Completion: 0%	25%	50%	75%	90%	Realized Costs
1966-1967	11	298	378	[illegible]	+ 109%	583	623
1968-1969	26	361	484	[illegible]	+ 194%	877	1,062
1970-1971	12	404	554	[illegible]	+ 248%	1,105	1,407
1972-1973	7	594	631	[illegible]	+ 218%	1,773	1,891
1974-1975[a]	14	615	958	[illegible]	+ 281 %	2,160	2,346
1976-1977[a]	5	794	914	[illegible]	+ 269 %	1,937	2,132

Source: DOE/EIA (1986): Analysis of nuclear power plant construction costs

Weighted average: **+ 207 %**

Unsuccessful Estimates of Lead-Times in the U.S. (1966-1977)

Table ES2. Average Estimated and Realized Lead-Times of Nuclear Power Plants by Year of Construction Start
(Months)

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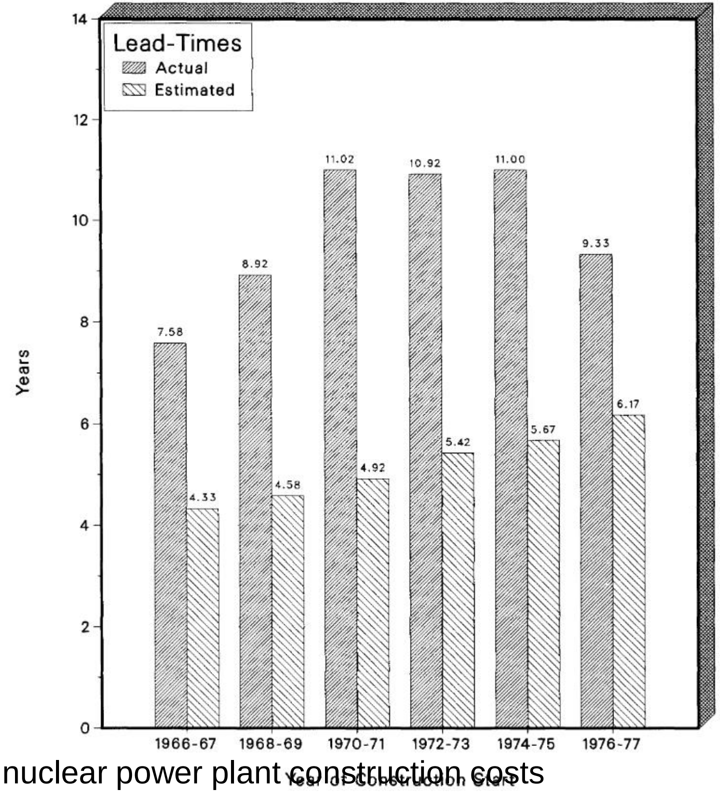
	0%	25%	50%	75%	90%	
1966-1967	52	56	65	+ 75%	82	91
1968-1969	55	63	72	+ 95%	91	107
1970-1971	59	77	92	+ 123%	110	132
1972-1973	65	87	96	+ 102%	115	131
1974-1975[a]	68	93	105	+ 94%	123	132
1976-1977[a]	74	92	95	+ 51%	100	112

Source: DOE/EIA (1986): Analysis of nuclear power plant construction costs

Weighted average: **+ 94 %**

Lead Times in the U.S. (1966 - 1977)

Figure 2. Actual and Estimated Lead-Times of Nuclear Power Plants in Operation by the End of 1986



Source: DOE/EIA (1986): Analysis of nuclear power plant construction costs

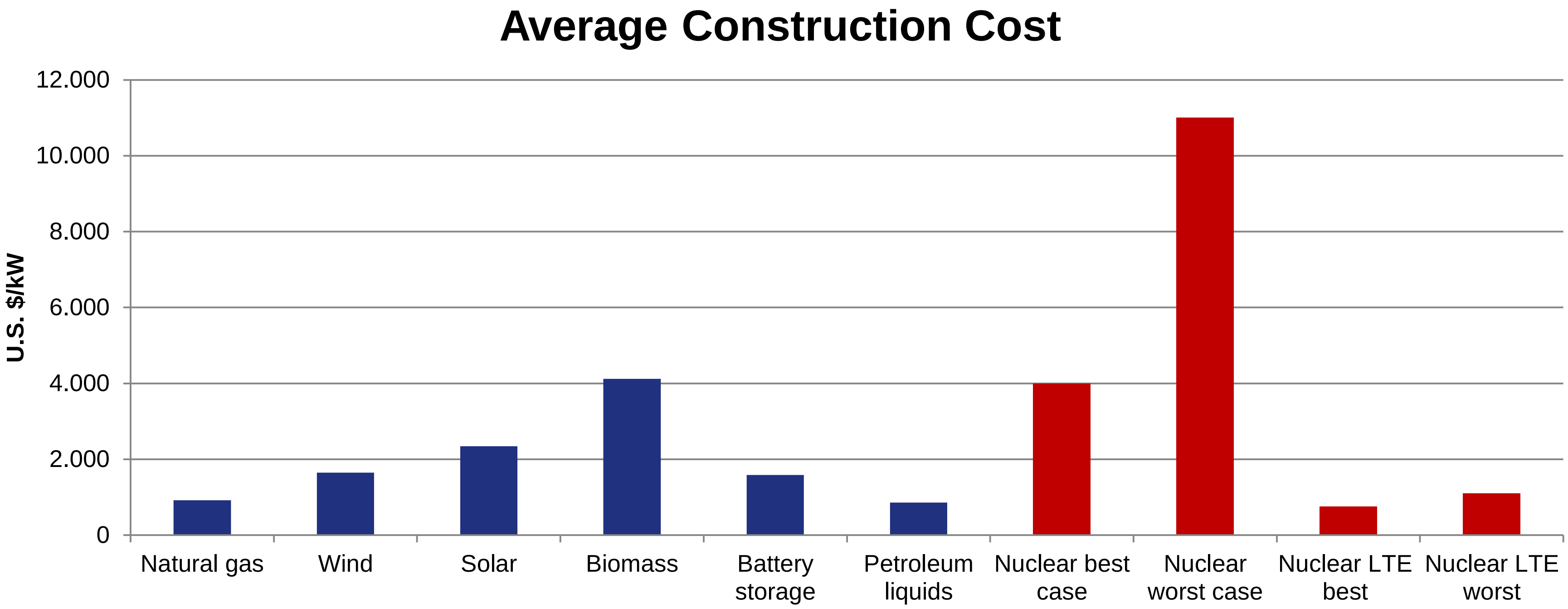
Cour de Comptes (2012) vs. Koomey et al. (2017)

	Cour de Comptes (2012)	Koomey et al. (2017)
Construction-related engineering and labour costs and pre-operating charges	0	EUR_{2010} 10 billion
Total OCC of 58 currently operative units (62,510 MW)	EUR_{2010} 72.862 billion	EUR_{2010} 83 billion
Total IDC paid for 58 currently operative units	EUR_{2010} 13 billion	EUR_{2010} 23 billion (reported by EDF)
Total Construction Costs of 58 currently operative units (62,510 MW)	EUR_{2010} 85.862 billion	EUR_{2010} 106 billion
Cost per MW	EUR_{2010} 1,165,606	EUR_{2010} 1,695,729
%	100 %	131.1 %

Heck et al. (2016): Monte-Carlo-Simulation for LCOE – Assumptions

Inputs	Coal	NGCC	Natural Gas	Nuclear	Wind	Solar PV	Solar thermal
Capital Costs [USD/kW]	1584-8071	559-1858	600-1200	4146-8691	1270-2670	1554-5000	4250-9000
Interest rate [% p.a.]	5	5-15	5-15	10	10	10	10
Loan period [years]	40	20	20	40	20	20	40
Fixed O&M [USD/kW p.a.]	19.67-30.80	5.5-15.37	4.9-24.3	54.19-121.19	12-60	7.28-34.72	46.98-79.48
Fuel costs [USD/MMBtu]	1.27-2.41	3.42-9.02	3.42-9.02	0.65	-	-	-
Heat rate [Btu/kWh]	8755-12055	6430-7050	9000-10850	10420-10480	-	-	-
Variable O&M [USD/MWh]	2.2-6.1	1.41-3-73	3.05-16.22	0.42-2.14	5.85-21.5	-	0.71-3
Capacity factor [%]	93	40-87	5-10	85-90	22.75-50.75	15.48-28	20.5-43-5
Carbon emissions [lbs/MMBtu]	214	117	117	-	-	-	-

Average Construction Cost of Different Technologies



Source: OECD/NEA (2012), European Commission (2016), EIA (2019), IEA (2019),

Heck et al. (2016): Monte Carlo Simulation of LCOE

Probability that top row LCOE is greater than left column LCOE	NGCC	Gas peaking	Nuclear	Wind	PV solar	Solar thermal
Coal	34%	~100%	77%	60%	96%	~100%
NGCC		~100%	95%	79%	99%	~100%
Gas peaking			0%	0%	23%	64%
Nuclear				28%	93%	~100%
Wind					96%	~100%
PV solar						83%

Source: Heck et al. (2016).

- In 95 % of the scenarios NGCC is cheaper than nuclear.
- In 77 % of the scenarios coal is cheaper than nuclear.
- In 72 % of the scenarios wind is cheaper than nuclear.

However:

- In only 7 % of the scenarios PV Solar is cheaper than nuclear.
- In none of the scenarios Solar thermal is cheaper than nuclear.

SMRs: Basic Resource and Fuel Requirements

	Standard LWR (50 MWd/kg)	**iPWR (30 MWd/kg)**	**LLC SMR (Fast Spectrum, Once Through)**
Uranium requirements (to make fuel)	6,200 tonnes (reference)	10,320 tonnes (67% increase)	2,910 tonnes (53% reduction)
Fuel demand	540 tonnes (5%-enriched fuel)	900 tonnes (5%-enriched fuel)	102 tonnes (12%-enriched fuel starter fuel)
Enrichment	3.90 million Seperative Work Units (SWU) (reference)	6.48 million SWU (67% increase)	2.19 million SWU (44% reduction)
Plutonium inventory in spent fuel	6.5 tonnes (12 kg/t of fuel)	8.1 tonnes (9 kg/t of fuel)	14.0 tonnes (69 kg/t of fuel)
Waste volume	540 tonnes (reference)	900 tonnes (67% increase)	240 tonnes (38% reduction)

The reference is set by a standard LWR (1000 MWe). For comparison, the analysis calculates with 5xiPWR (5x200 MWe) and 5xLLC (5x200 MWe). All numbers are scaled to a power generation of 1000 MWe for 9000 effective full-power days (e.g. 30 years with a load factor of 82%).

Data are computed using the Monte Carlo neutron transport Code MCNP and the ORIGEN2 point-depletion code.

Source: Glaser et al. (2013)