Insights into Nuclear and SMR Economics

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Perspective matters...

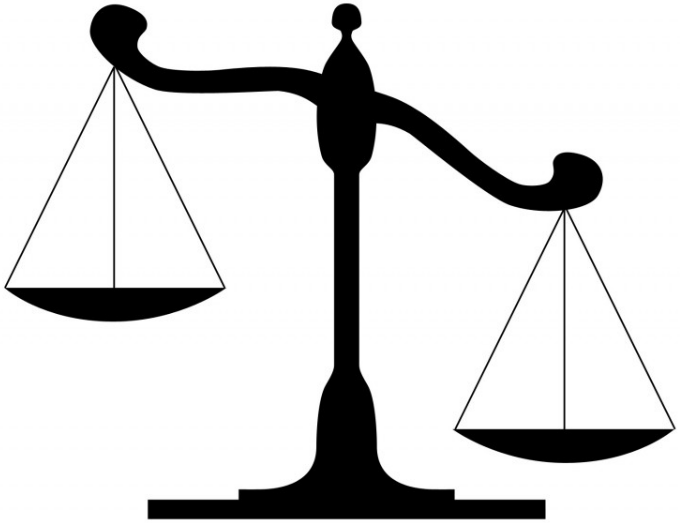
Project Developer

Project developers rely on standard financial appraisals focusing on *returns to shareholders*.

Public Sector Decision-Maker

Economic appraisal takes a broader view to include *benefits and costs to society*.

Illustration: huffpost.com
https://www.huffpost.com/entry/its-all-perspective_b_11688054



Costs have to be balanced against benefits

Investments in energy infrastructures are driven by specific challenges:

Security and reliability of supply

Growing penetration of power generation from variable renewable energy (VRE) sources (increasing need to balance VRE)

Affordable energy prices for consumers

Global concerns for climate change (need of progressively substituting fossil-based energy fuels with more sustainable sources)

Cost-benefit analysis: A method to evaluate the net economic impact of a project. Expected benefits are estimated and monetised with inflation accounted for, and offset against project costs. The approach is most commonly used to inform in major infrastructure investment in both developed and developing countries.

Cost-effectiveness analysis: This method is used where monetising outcomes is not possible or appropriate, most commonly in health. Common measures include "quality-adjusted life years".

Value for money and international development: Deconstructing myths to promote a more constructive discussion Penny Jackson, OECD Development Co-operation Directorate.

https://www.oecd.org/development/effectiveness/49652541.pdf

Multi-billion investments in multi-billion infrastructure projects in general, and nuclear newbuilds in particular, are a synonym of economic growth and job creation over many decades.

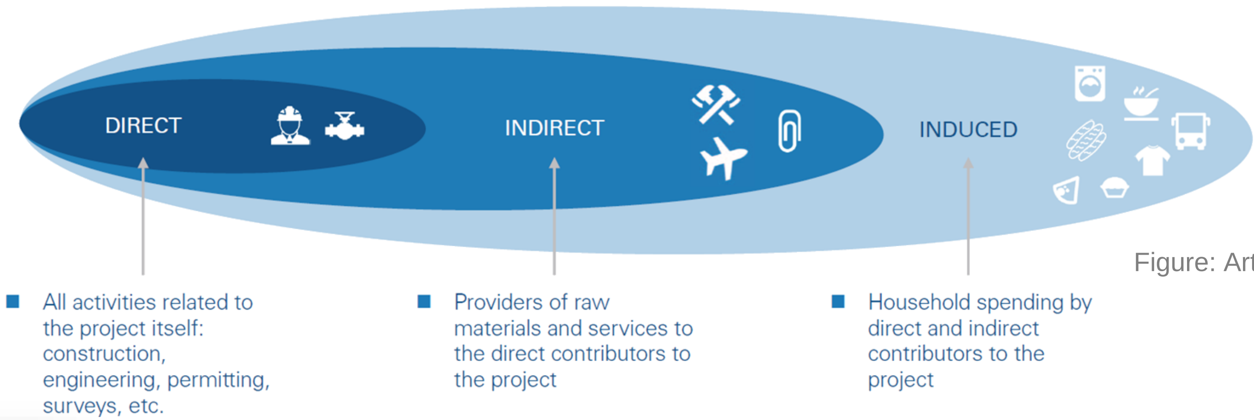
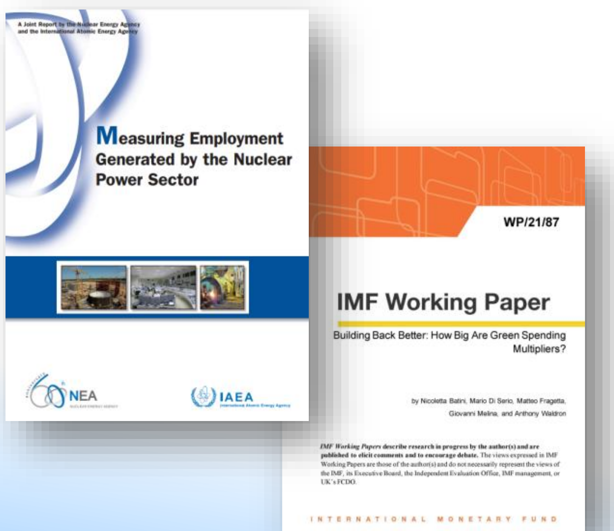


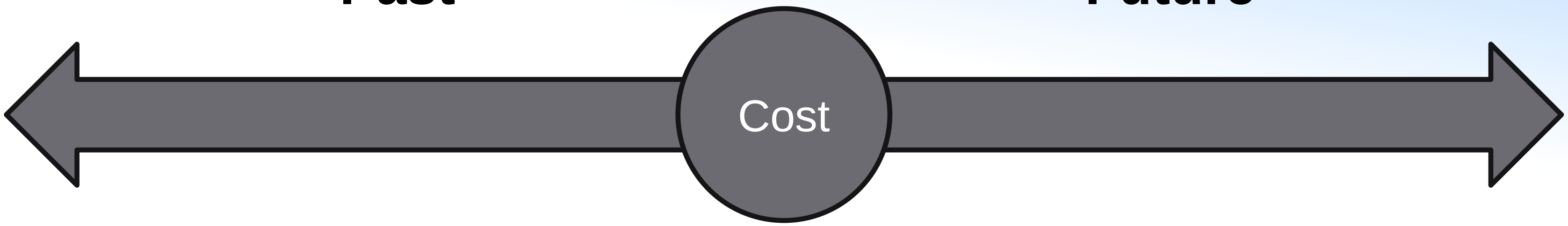
Figure: Arthur D. Little



Investments in energy infrastructures tend to stimulate construction, manufacturing, engineering services, generating economic growth across a wide range of economic sectors, beyond the energy sector.

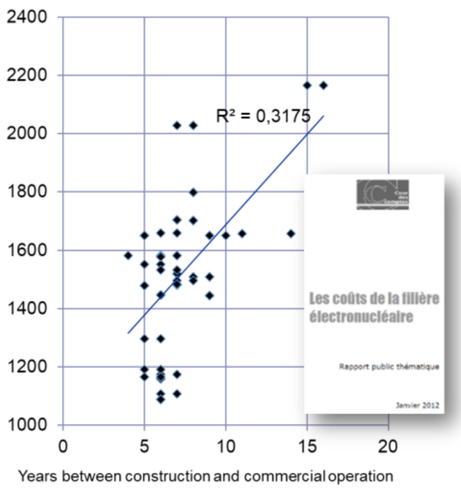
The labour market is also impacted by direct and indirect (or “spillover”) effects, which can be estimated and quantified.

Past **Future**

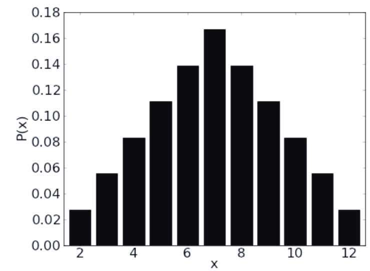


Known / Certain

French Reactors' Overnight Construction Costs ($2015)



Unknown / Uncertain



We can only approximate the probable cost of a program, project, system, equipment, part or task.

Example of a CBS for a 2 x 1000 MWe NPP

Cost Item	%
Buildings and Structures	13,1%
Nuclear Island Equipment	**14,5%**
Turbine Island Equipment	**13,5%**
Electrical and I&C Equipment	**13,4%**
Water Intake and Heat Rejection	2,8%
Auxiliary Equipment	6,2%
Simulator	0,5%
Construction Labor	10,3%
Engineering & Design	6,5%
Project Management	5,6%
Construction Supervision	1,9%
Start-up and Commissioning	2,8%
Personnel Training	0,5%
Site Infrastructure	1,9%
Owner's Costs	6,5%
TOTAL:	100%

Example of a CBS for a 2 x 1000 MWe NPP to be built in a brownfield site in Eastern Europe.

Shared by Mr. O. A. Mignone (Italy) during an IAEA Consultancy Meeting held in Vienna in January 2019.

Cost distribution in % of the total overnight cost, allows to see at a glance the typical cost components weight in the overnight cost.

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Reactor building equipment	**2,7%**
Reactor	1,3%
Reactor internals	0,8%
Reactor foundations	0,2%
Internal reactor control system	0,5%
Equipment of the primary circuit	**5,5%**
Reactor coolant pump and its auxiliary systems	1,1%
Steam generators	3,5%
Pressurizer	0,3%
Other	0,7%
Auxiliary reactor systems	**2,3%**
Waste management systems	**1,3%**
Fuel-handling systems	**0,8%**
Other	**1,9%**

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TOTAL:	100%

Turbine building equipment	**7,3%**
Generator	**2,0%**
Condensate system	**2,0%**
Main steam pipes and feedwater system	**1,3%**
Auxiliary systems	**0,9%**

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TOTAL:	100%

Generator circuit-breakers, M&LV switchgears…	**1,0%**
Diesel generators	**0,7%**
Auxiliary systems	**4,8%**
Transformers	0,4%
Unit transformers	0,1%
Unit auxiliary transformers	0,3%
LV transformers	0,1%
Cables and cable penetrations	3,1%
Cable trays	1,0%
Connection system	**0,4%**
Instrumentation and Control (I&C)	**6,5%**

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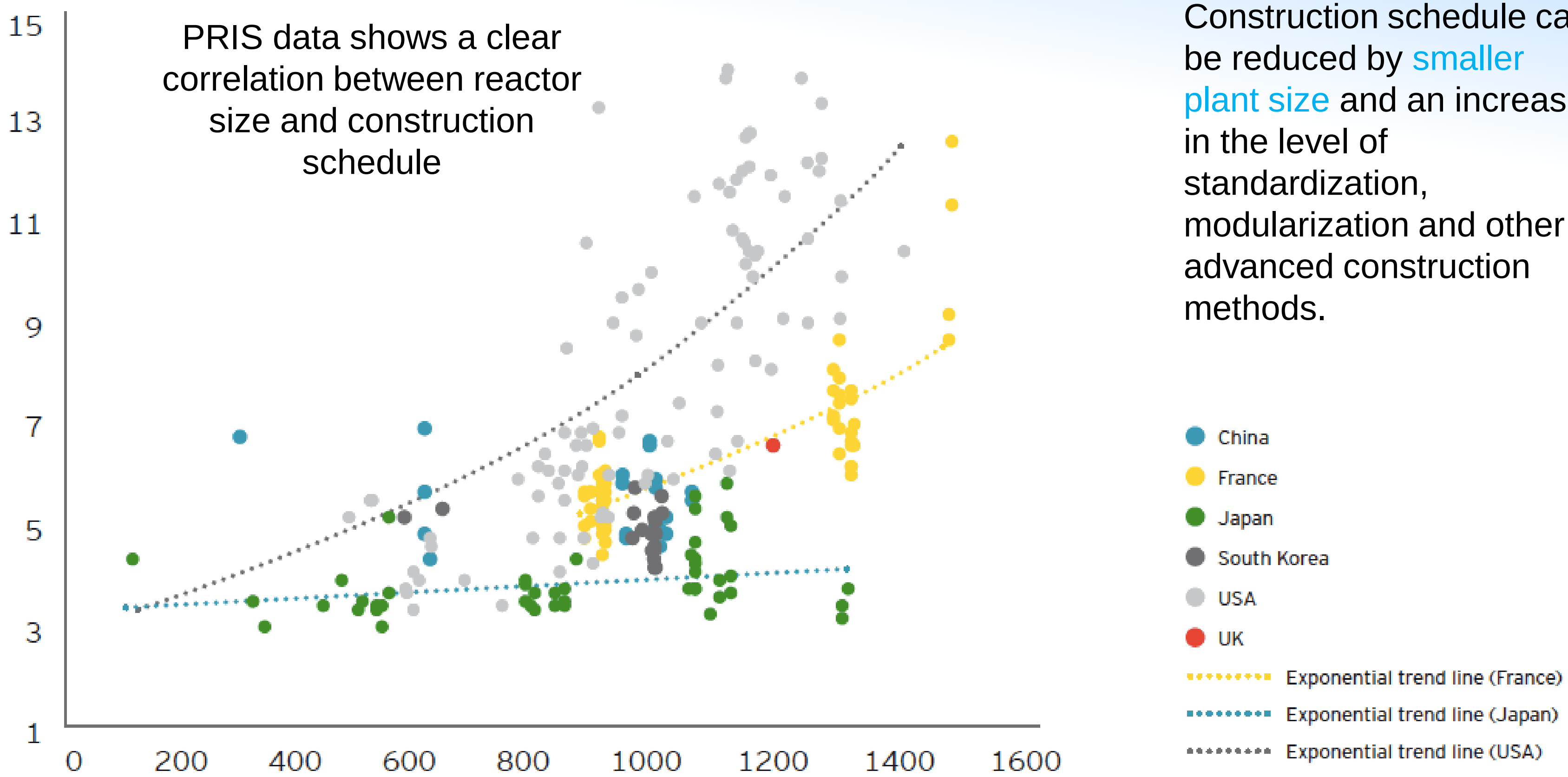
Construction Delivery Time



Construction schedule can be reduced by smaller plant size and an increase in the level of standardization, modularization and other advanced construction methods.

Schedule length is often heavily influenced by regulation

Figure: Small Modular Reactors: Techno-Economic Assessment
https://www.gov.uk/government/publications/small-modular-reactors-techno-economic-assessment

Recurring Costs

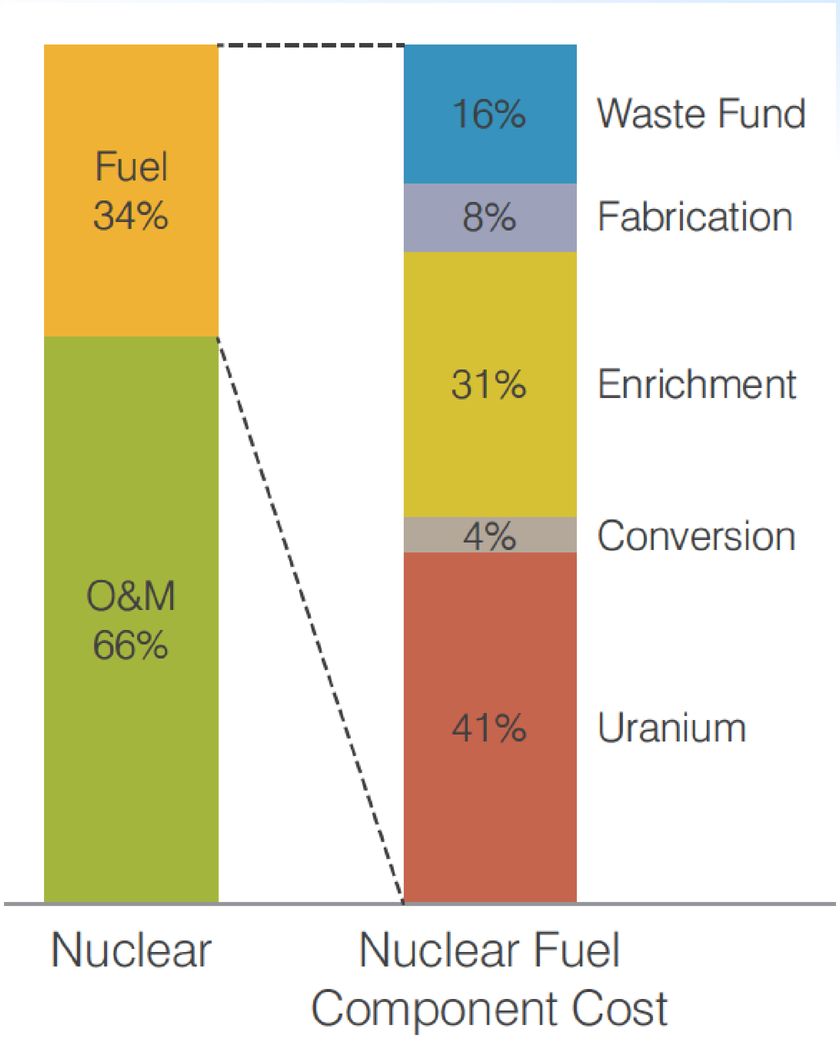
Once the NPP is built, fuel and O&M costs are low and stable.

Most of the recurring costs are fixed costs and related to O&M

O&M costs depend very much on the age of the plant, with a tendency for O&M to rise as plants get older.

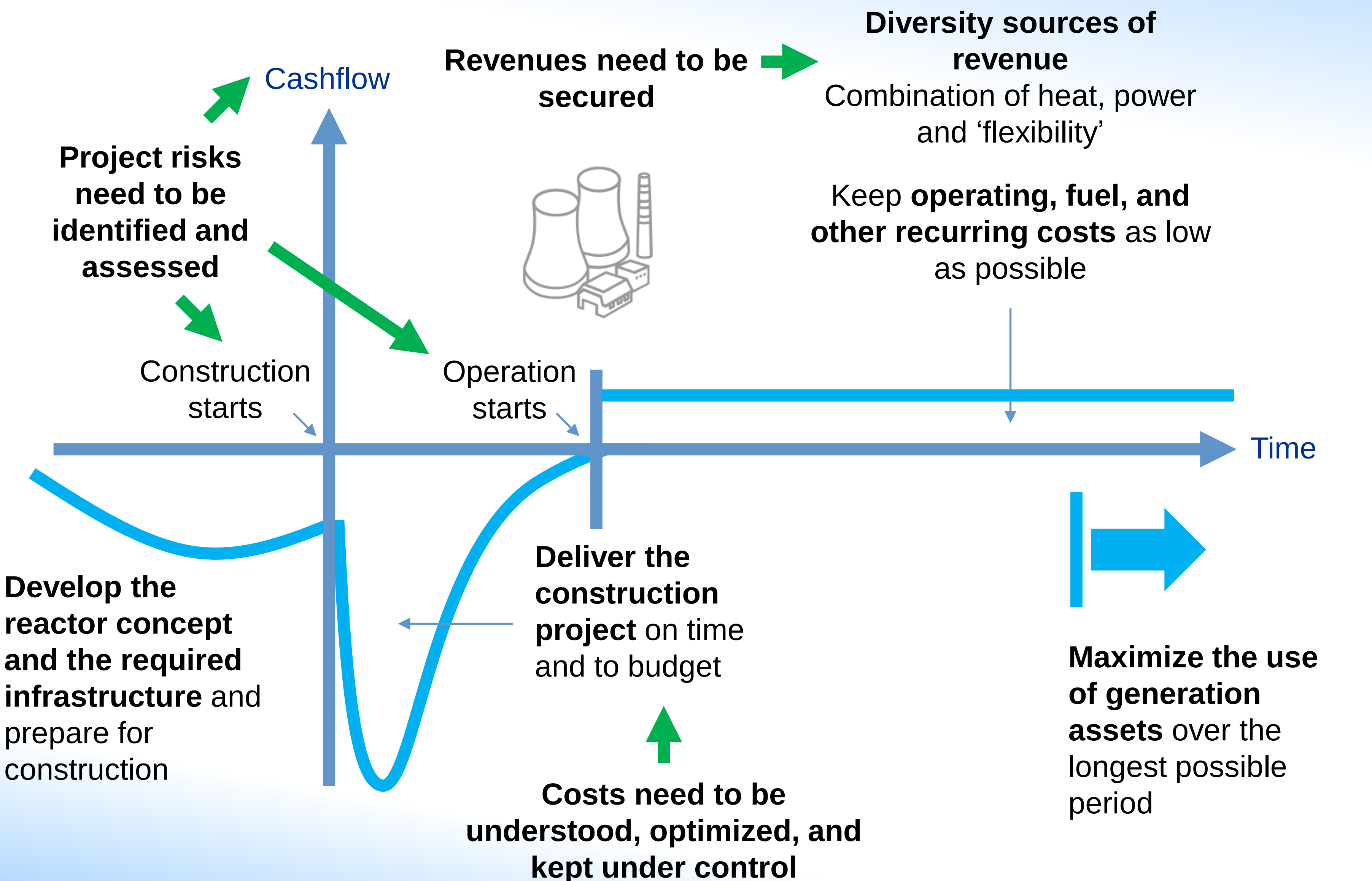
O&M costs are particularly influenced by regulatory requirements.

Labour is – in most cases – the biggest contributor to O&M costs.



Graph: NEI, WNA

Financing Costs



Human Resources
Information Technologies
Legal Support
Scope of Works
Project Management
Finances and Cost Control
Procedures and Records

Political

Economic

Social

Internal

External

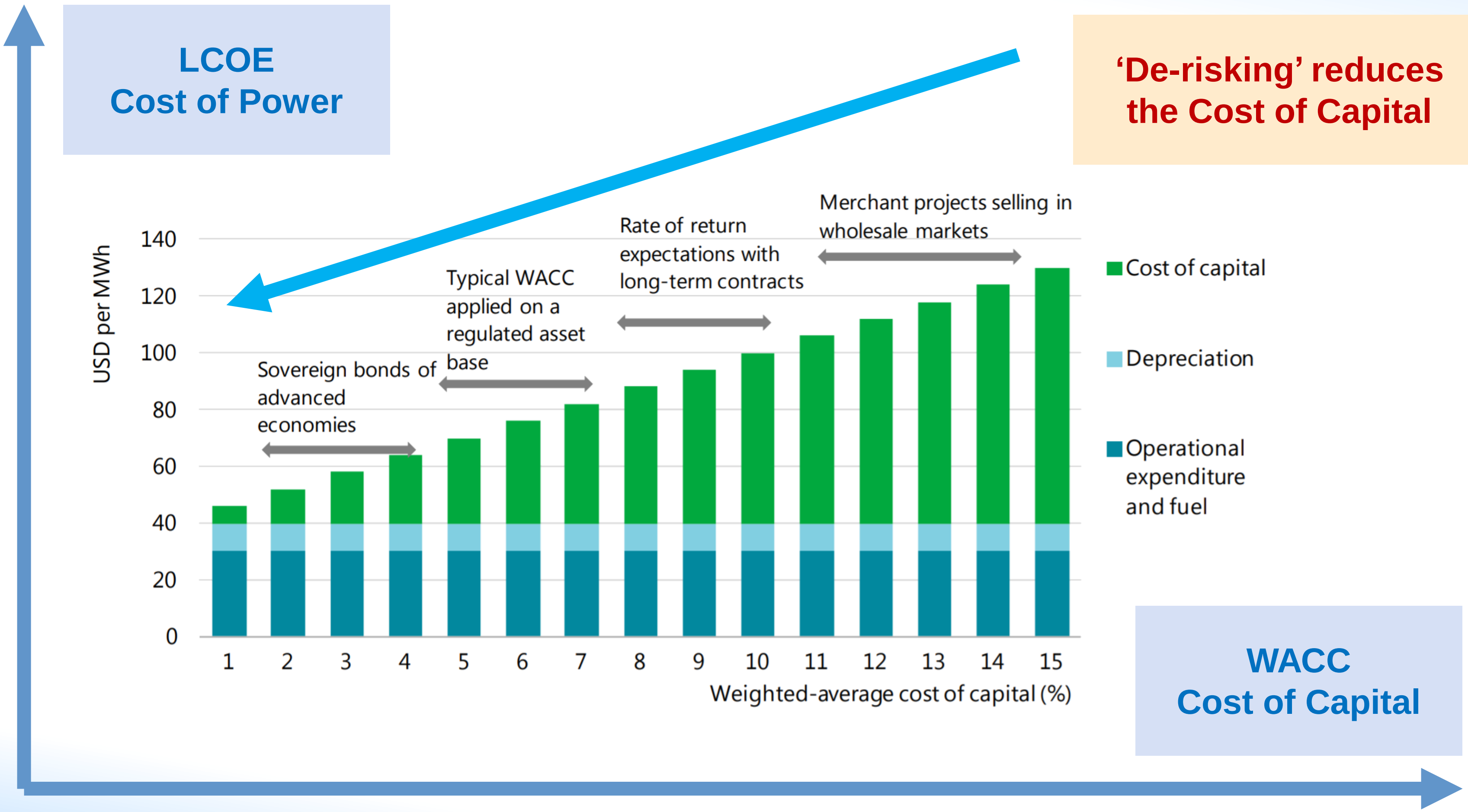
Licensing and Permits
Design
Equipment Manufacturing
Procurement
Construction Works
Tests and Tests Duration

Environmental

Technological

Legal

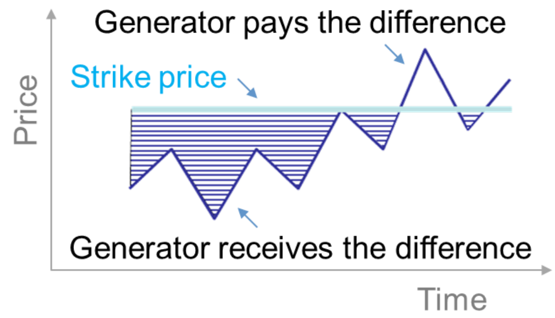
Access to cheap capital makes a huge difference to the cost of producing electricity for a new nuclear power project *



* IEA, Nuclear Power in a Clean Energy System (2019) https://www.iea.org/reports/nuclear-power-in-a-clean-energy-system

In the case of the HPC, the **Contract for Difference (CfD)** strike price 92.50 £/MWh to guarantee acceptable returns for EDF.

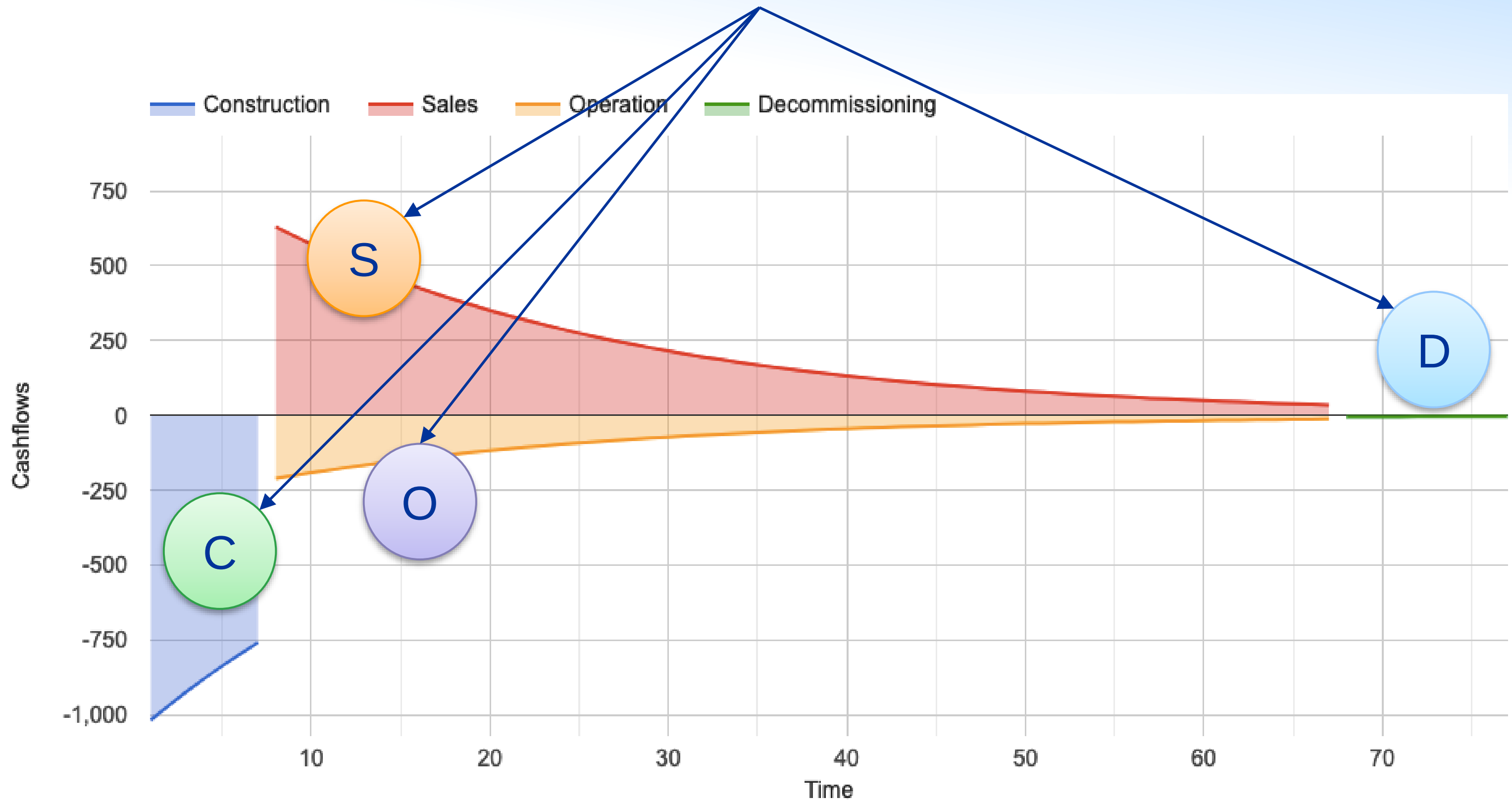
The UK government is considering the **Regulated Asset Base Model** for financing new nuclear projects.



As you meet various different points of construction, they trigger the ability to release some revenue *

* Tom Greatrex to power-technology.com (2019) https://www.power-technology.com/features/regulated-asset-base-model-uk-nuclear/

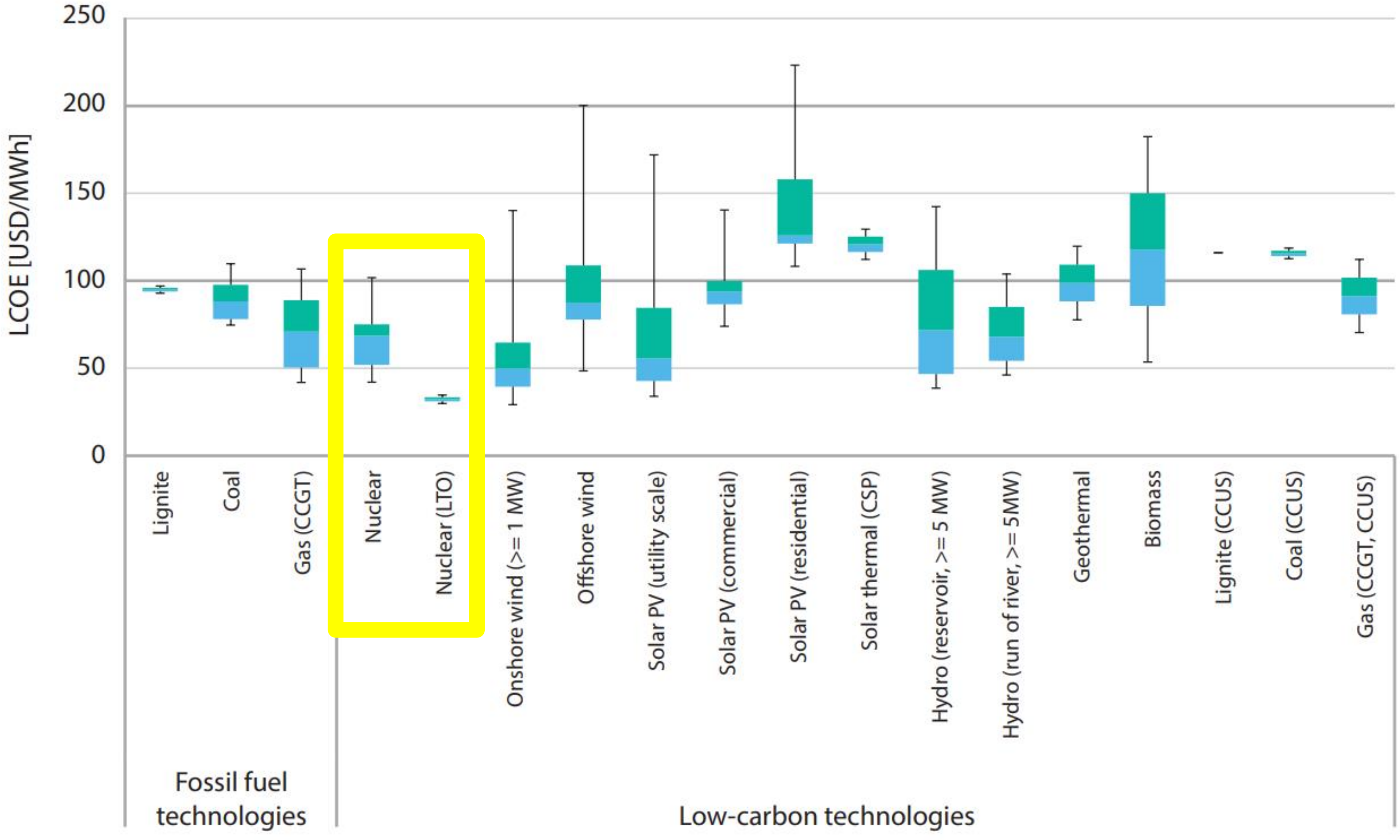
Present value of each phase = area under the curve = Σ of the discounted cashflows



The present value (PV) of future revenues should offset the PV of future expenses

Projected Costs of Generating Electricity - 2020 Edition

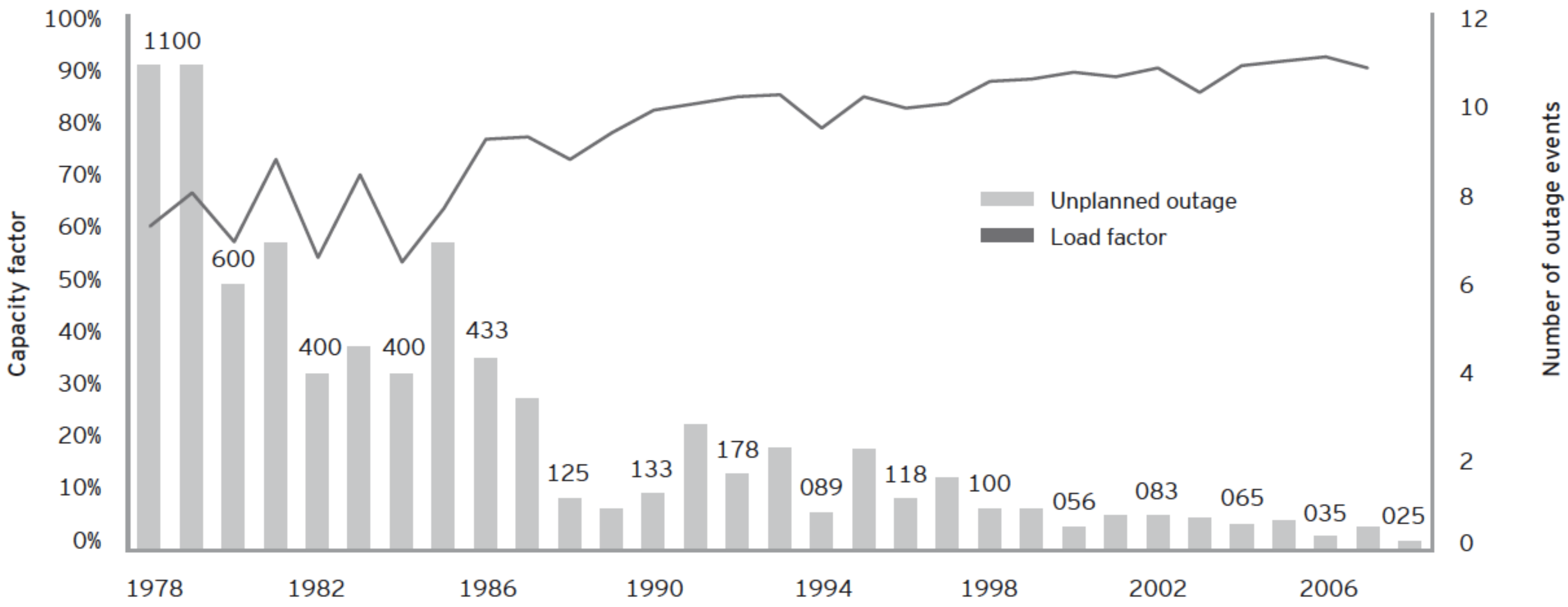
IAEA



Note: Values at 7% discount rate. Box plots indicate maximum, median and minimum values. The boxes indicate the central 50% of values, i.e. the second and the third quartile.

Illustration: Projected Costs of Generating Electricity - 2020 Edition
https://www.oecd-nea.org/jcms/pl_51110/projected-costs-of-generating-electricity-2020-edition?details=true

A reactor's capacity factor is important because it relates directly to the revenue that is generated by the plant.



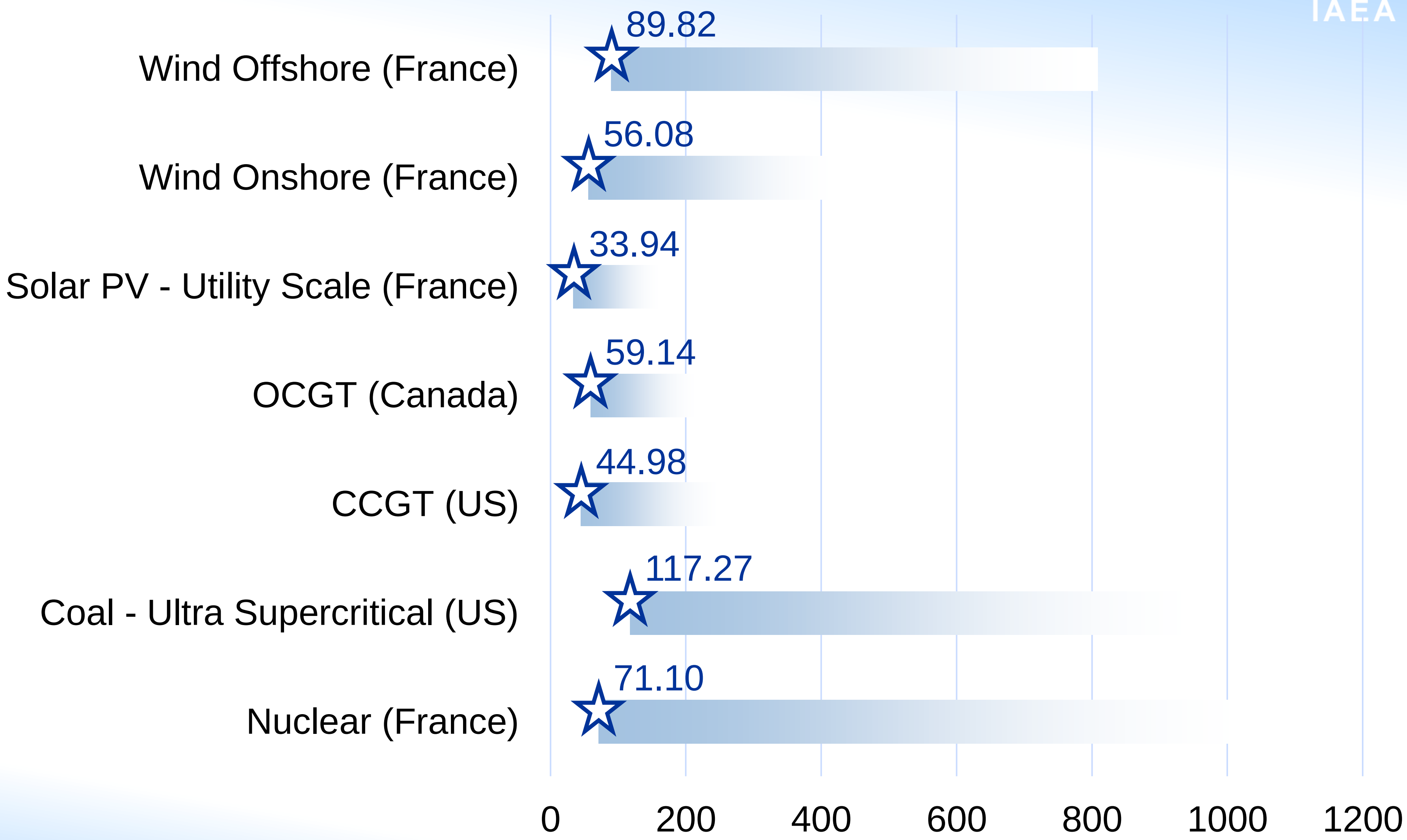
In South Korea, operational benefits have come from consolidation of operator utilities, standardization of reactor design and localization of the supply chain.

Figure: Small Modular Reactors: Techno-Economic Assessment
https://www.gov.uk/government/publications/small-modular-reactors-techno-economic-assessment

In grids with high shares of variable renewables, NPP capacity factors - and revenues from the sale of electricity - will be too low to offset generation costs.

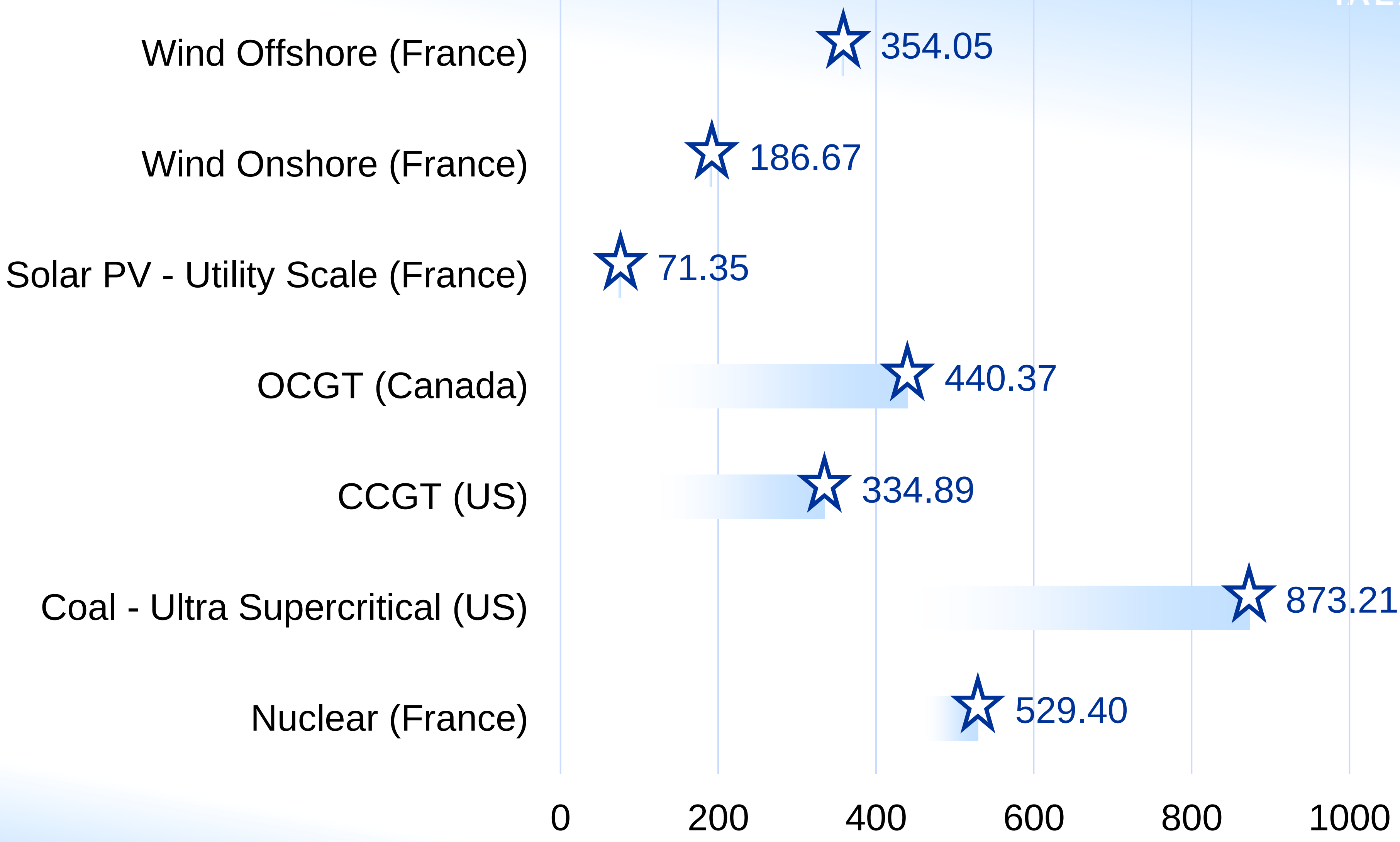
Getting paid for MWh - and MWh only - is not a viable business model not only for nuclear but also for all dispatchable technologies operating in load-following mode with a low capacity factor.

The value nuclear brings to such systems goes far beyond MWh. It should be acknowledged and rewarded to keep the industry thriving and investments flowing.



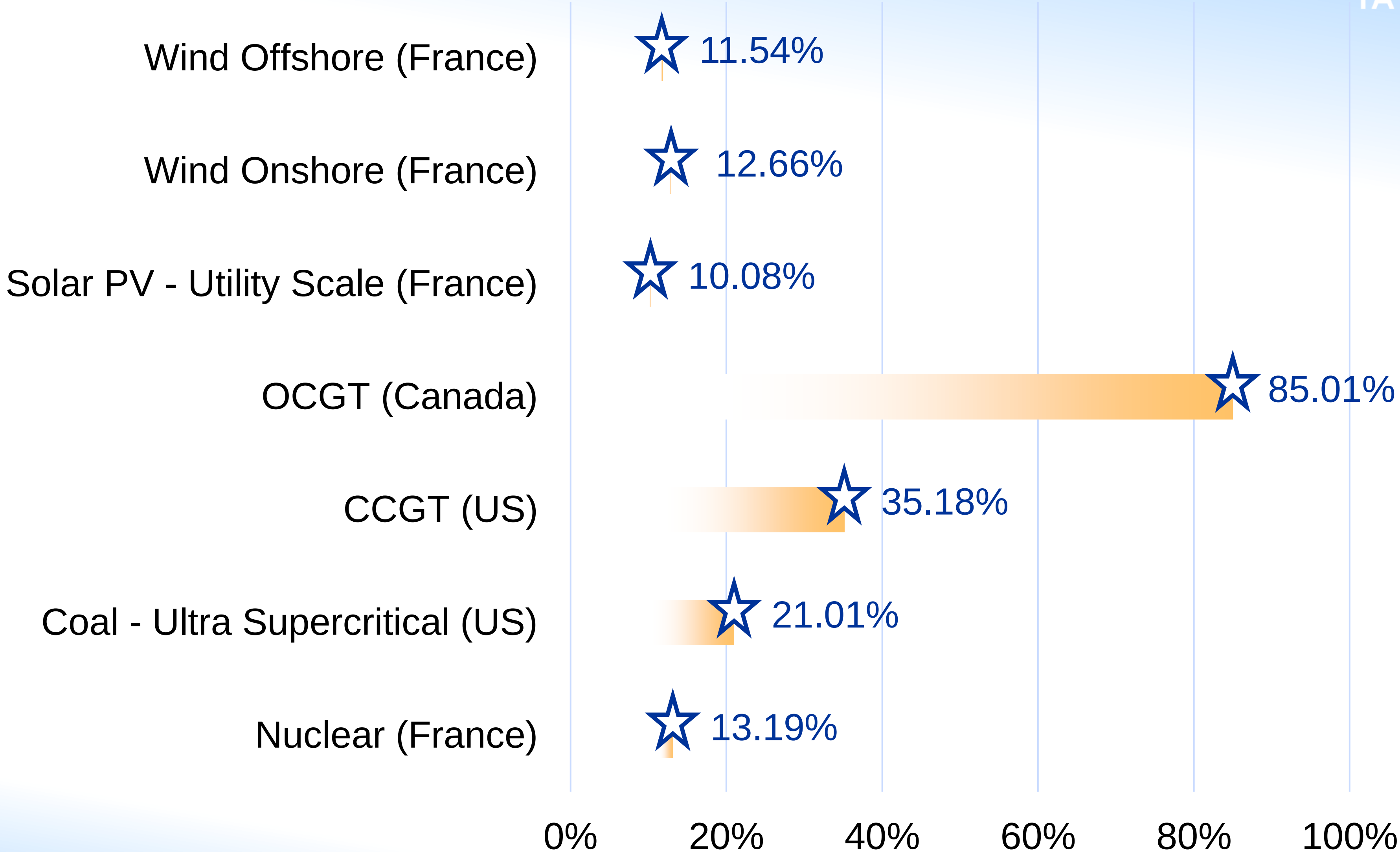
RR_{MWh} = LCOE

Revenue requirements ($) per MWh of electricity generated



RR_{kW}

Annual revenue requirements ($) per kW of generation assets



$RR_{\$AV}$
Revenue requirements per $ of generation asset value (%)

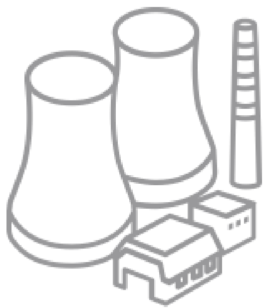
There is nothing new about small reactors ..

1954

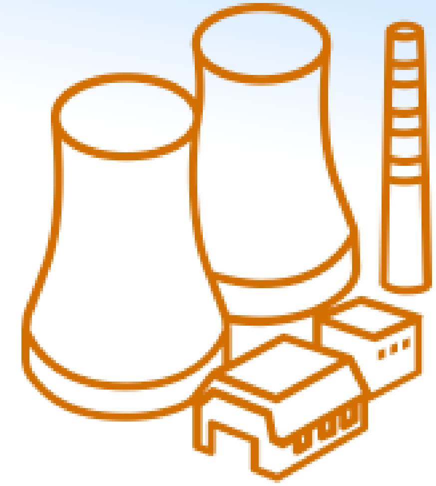
1954, Obninsk, Russia.
APS-1 with a net electrical output of 5 MW was connected to the grid.

SMRs have been powering submarines and aircraft carriers since USS Nautilus was launched in 1954.

Big is cheap and efficient ..



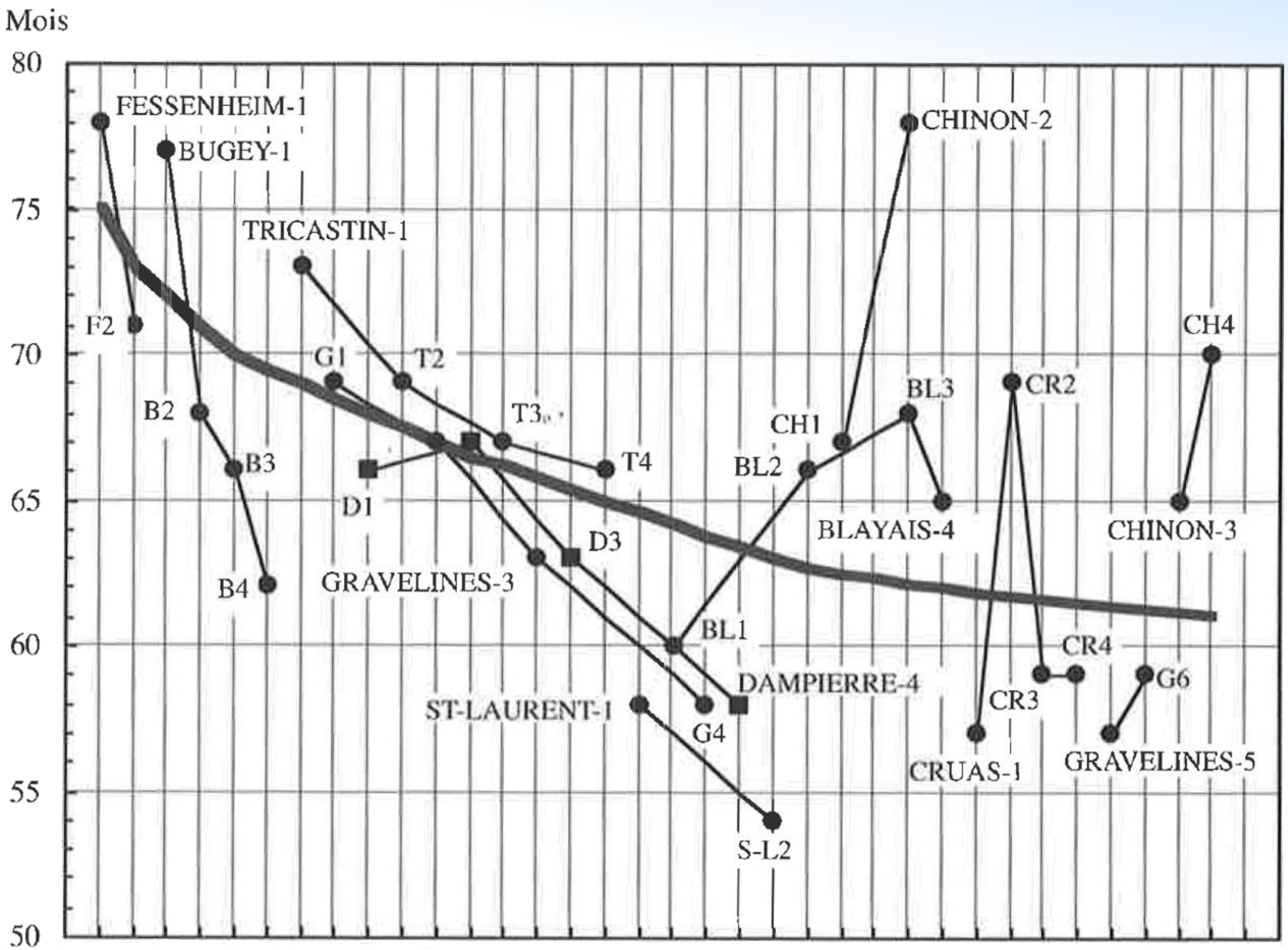
As a power plant gets larger in size, it gets progressively cheaper to add additional capacity.



REACTORS

Name	Type	Status	Location	Reference Unit Power [MW]	Gross Electrical Capacity [MW] ▲	First Grid Connection
BEZNAU-1	PWR	Operational	BEZNAU	365	380	1969-07-17
BEZNAU-2	PWR	Operational	BEZNAU	365	380	1971-10-23
MUEHLEBERG	BWR	Permanent Shutdown	MUEHLEBERG	373	390	1971-07-01
GOESGEN	PWR	Operational	DAENIKEN	1010	1060	1979-02-02
LEIBSTADT	BWR	Operational	LEIBSTADT	1220	1275	1984-05-24

As long as you keep building (and learning) ..



And sustain demand for nuclear systems and components

IAEA

The New York Times

Airbus A380, Once the Future of Aviation, May Cease Production

An A380 operated by Malaysia Airlines passing over London. The European aerospace company said on Monday the A380 was at risk of being discontinued. Matthew Childs/Reuters

By Jack Ewing

Jan. 15, 2018

“Airbus needs a minimum of six to eight orders a year to keep production alive at the A380’s final assembly plant near Toulouse.

https://www.nytimes.com/2018/01/15/business/airbus-a380-emirates.html

If providers of nuclear components and services close due to lack of orders, there will be a substantial loss of knowledge, experience, competencies and qualifications.

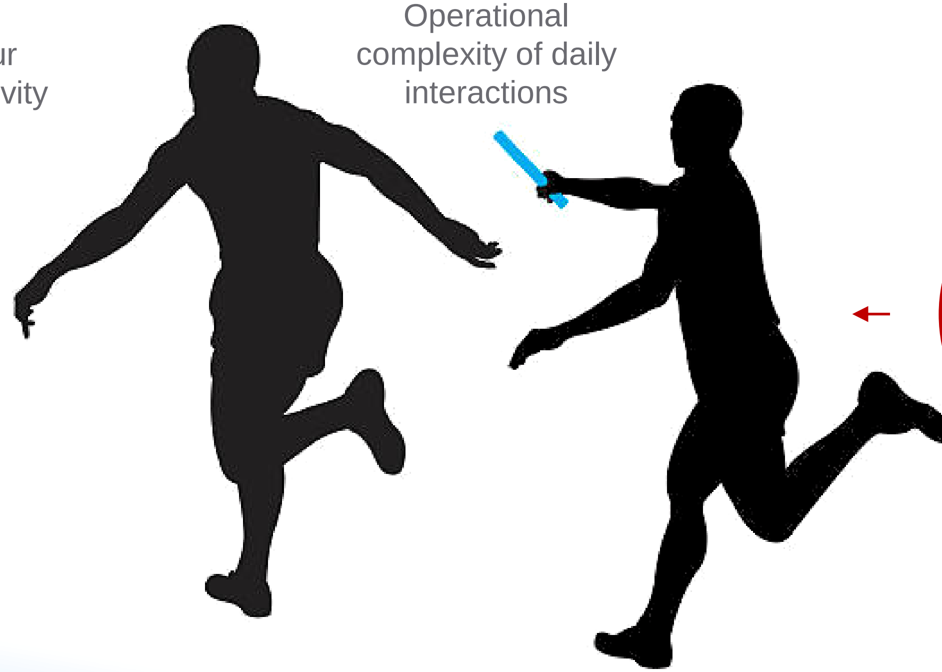
Relay race

Limitations in worker qualifications

Availability of highly engineered equipment

Labour productivity

Operational complexity of daily interactions



Who is the weakest runner?

A chain is only as strong as its weakest link

“Learning” brings costs down

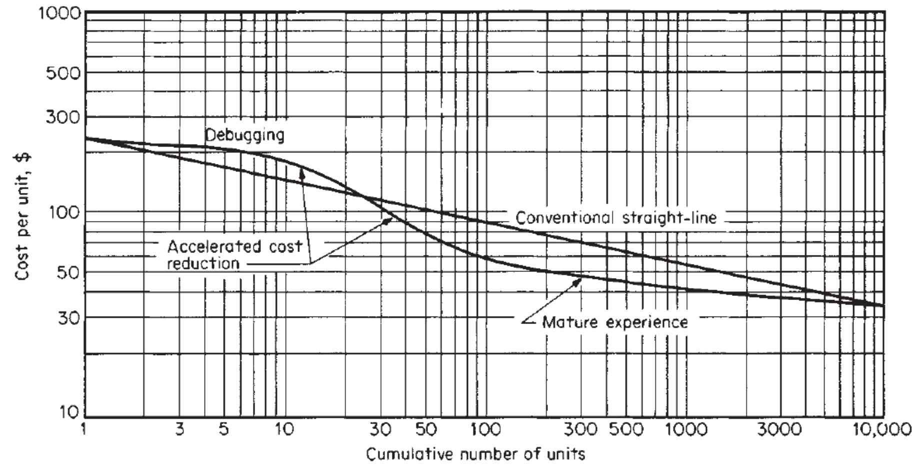
The time required to manufacture a product, the frequency of occurrence of defects - and the cost of production - associated with the same process (noted Y in the formulae below), tend to decrease as the number of units produced (noted X) increases (Wright's empirical law, 1936):

$$Y = K \,.\, X^{N}$$

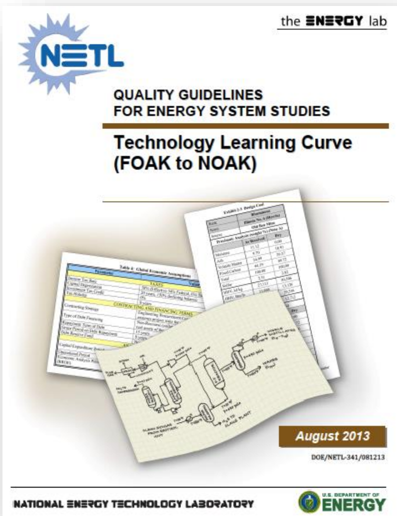
The log-log diagram shows an example of the evolution of the average unit cost as a function of the number of units produced. The straight line entitled "conventional straight-line" shows the evolution of Y as a function of X (Wright's formula) for a constant N, independent of X. In reality, the experience curve is rather "S-shaped" (Yeh, 2012), hence the deviations mentioned in the graph.

(Perry, 1999) : Perry, R. H., Green, D. W., Perry’s Chemical Engineers’ Platinum Edition, Editions McGraw-Hill, 978-0071355407 (ISBN13), 1999.

(Yeh, 2012) : Yeh, S. and Rubin, E. S., A review of uncertainties in technology experience curves, Energy Economics, Vol. 34, No. 3 (2012), pp. 762-771, 2012.



Technology learning curve of fossil fuel power plants



Level of Maturity	R - Value
Experimental (FOAK)	0.06
Promising, 2nd	0.05
Growing, 3rd & 4th	0.04
Proven, 5th to 8th	0.03
Successful, 9th to 16th	0.02
Mature, 17th & more	0.01

The learning rate decreases as more plants are constructed and operated

SMR economic principles *

SMRs achieve their economic advantages based on economies of series, modularity and standardization for commercial deployment.

This could allow the nuclear industry to be more like the airline or shipbuilding industry in terms of deployment model.

A fleet approach would see favourable SMR designs build in series, promoting standardization and learning-by-doing through the building of subsequent, identical units.

O&M economies of scale are stronger than capital:

- A 100 MW plant will not use 1/10 the staff of a 1,000 MW plant.
- Need to disrupt the operating procedures compared to larger plants.
- Simpler, less maintenance, less operators.
- Belief is that O&M can be maintained on $/MWh basis, but not yet proven.
- Required regulatory engagement.

Fuel costs can vary by design:

- A little higher for SMRs compared to PWRs (lower core dimensions → poor neutron economy).
- Advanced fuels vary in cost and more assessment is required.

* Milt Caplan, MZConsulting Inc,

Modular construction

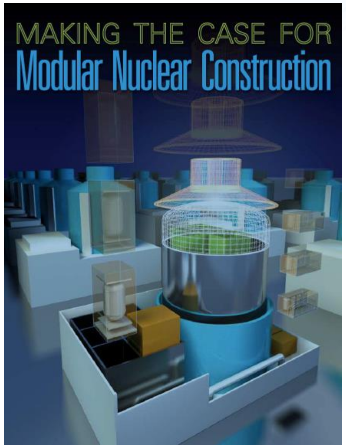
Transportable modules are manufactured in factories, assembled at the on-site assembly area into super modules (SMs).

SMs are then lifted to the construction site and integrated with the other SMs to complete the Nuclear Island.

A rule of thumb derived by the shipbuilding industry, the labor time of carrying out a task at the construction site will be approximately 8 times longer than the time of carrying out the same task in the factory.

In-factory fabrication allows cost reduction and improved quality and safety, but requires an earlier cash flow compared to the standard stick construction process.

On site SMs assembly allows a higher level of parallelism with a subsequent shortening of the construction schedule.



"We need to make sure the NRC understands the efficiencies we hope to gain by doing much of the inspection and testing on the modules at the factory, before they come to the site.

The nuclear industry needs to make the case that items assembled and tested in the factory can be as safe and reliable as those built and tested on site.

Maronati and Petrovic, Total Capital Investment Cost Evaluation of SMR Modular Construction Designs (2016)

EPRI journal (2010)

Co-siting

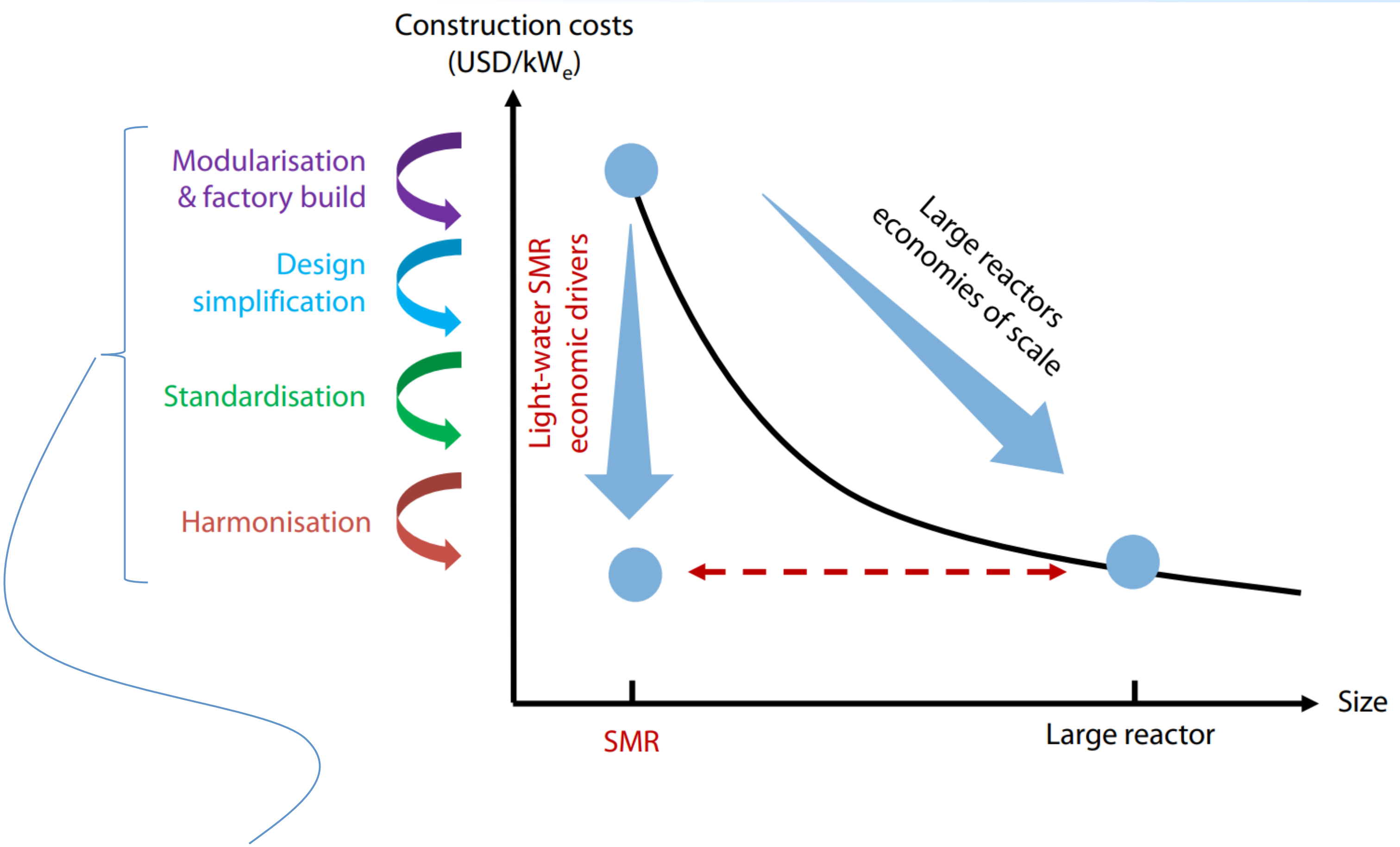
Installing multiple reactors on the same site at the same time or in close succession

Capex reductions: up to 14% *
Marginal costs (per unit) reduction: up to 15% *

Co-siting economies mainly impact indirect costs from setup activities and site infrastructure, such as site licensing, land acquisition and connection to the transmission network.

* Small Modular Reactors: Techno-Economic Assessment
https://www.gov.uk/government/publications/small-modular-reactors-techno-economic-assessment

Balancing diseconomies of scale



Already proven in other industries, e.g., shipbuilding, aircraft industry.

Illustration: Unlocking Reductions in the Construction Costs of Nuclear A Practical Guide for Stakeholders
https://www.oecd-nea.org/jcms/pl_30653/unlocking-reductions-in-the-construction-costs-of-nuclear?details=true

IAEA

thank you!