

Nuclear Energy's role in a Renewable Energy System (NERES)

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The Nuclear Energy's Role in a Renewable Energy System (NERES) Project

Core objectives of the project

Timeline: 3 years

A. Power System Studies: Study how expansion of nuclear energy in the Nordics affects the power system

1. Power System Investment Modelling
2. Power System Market Modelling
3. Nuclear Energy Project Finance Studies
4. System Costs
5. Nuclear Fusion Potential Study

B. Hydrogen Opportunity Studies: Investigate hydrogen/synfuels production from nuclear energy.

1. Hydrogen Production from Nuclear Energy
2. Hydrogen from Thermochemically Splitting of Water
3. Synthetic Fuels

The team



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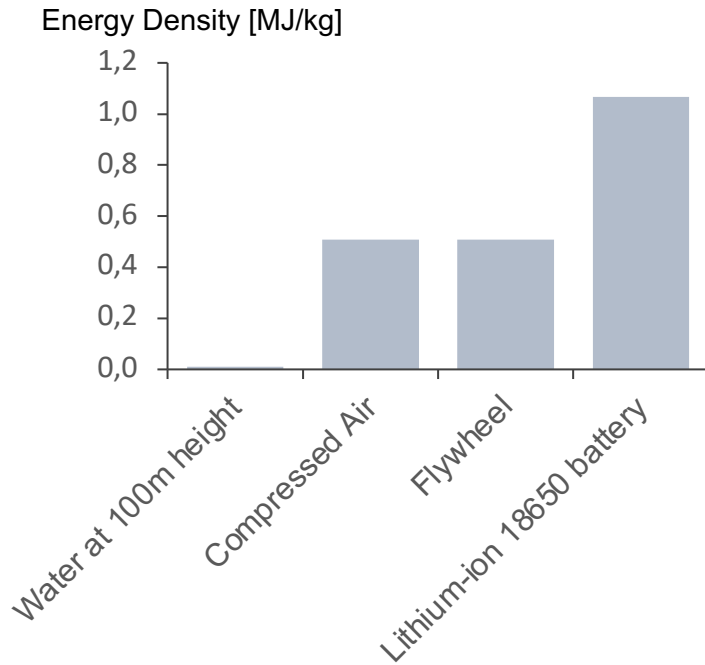


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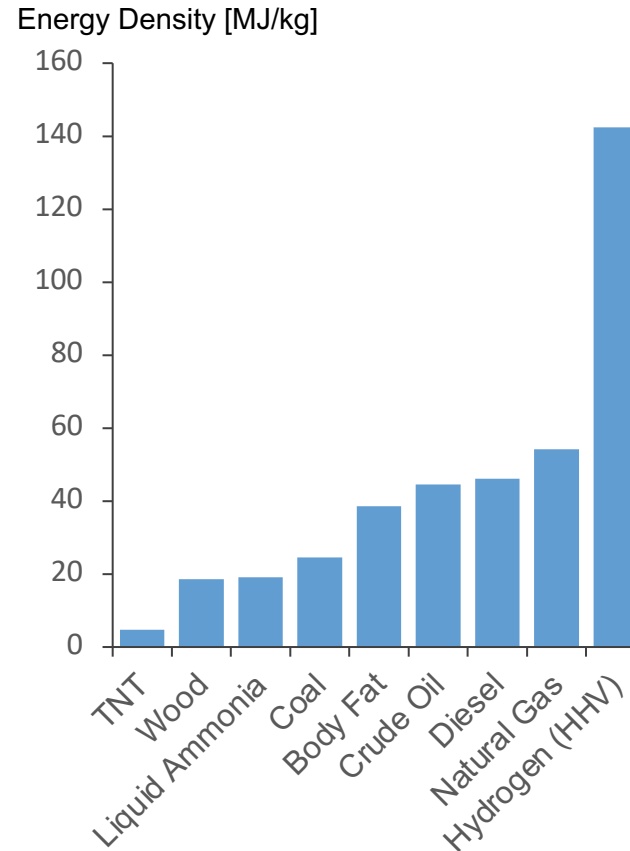
Why is nuclear energy interesting?

Energy density of nuclear energy is 1 000 000 times greater than energy based on chemical bonds.

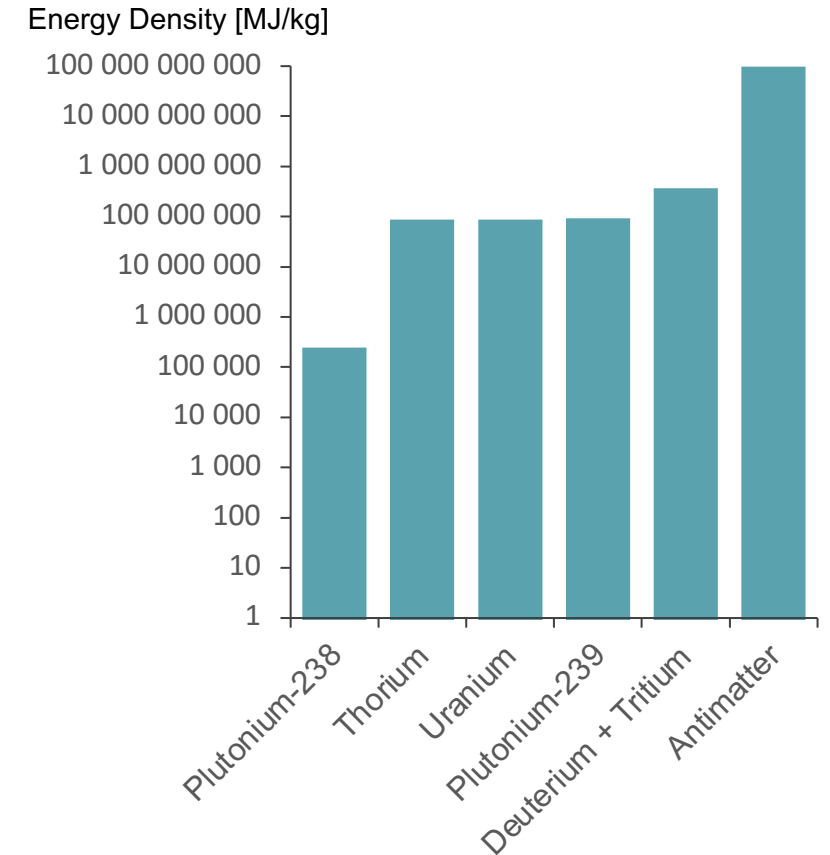
Energy density of storage technologies ...



... lags energy stored in fuel..



... but nuclear energy knocks them all out of the park

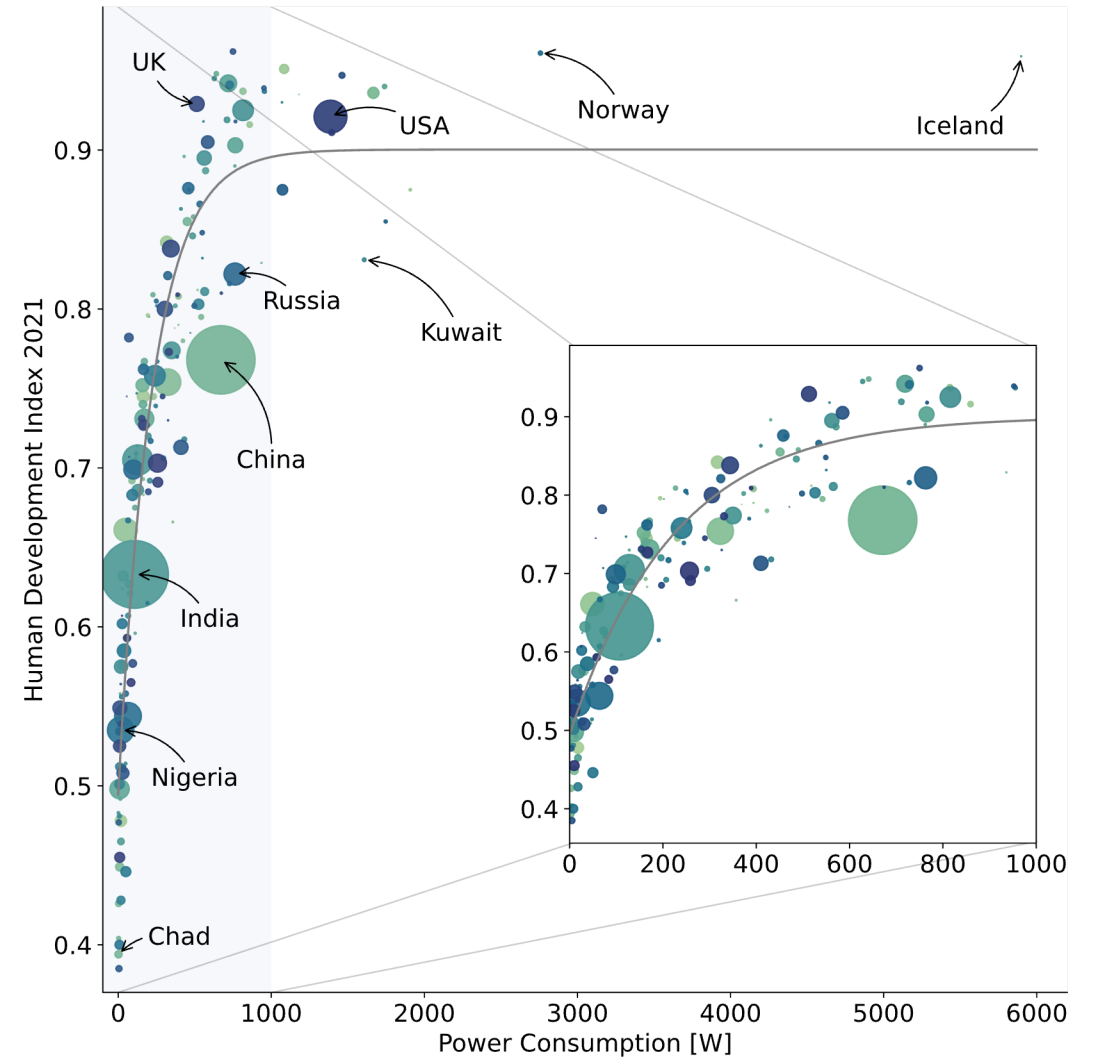


Source: (Energy Density)

For human prosperity, the world needs more electricity.

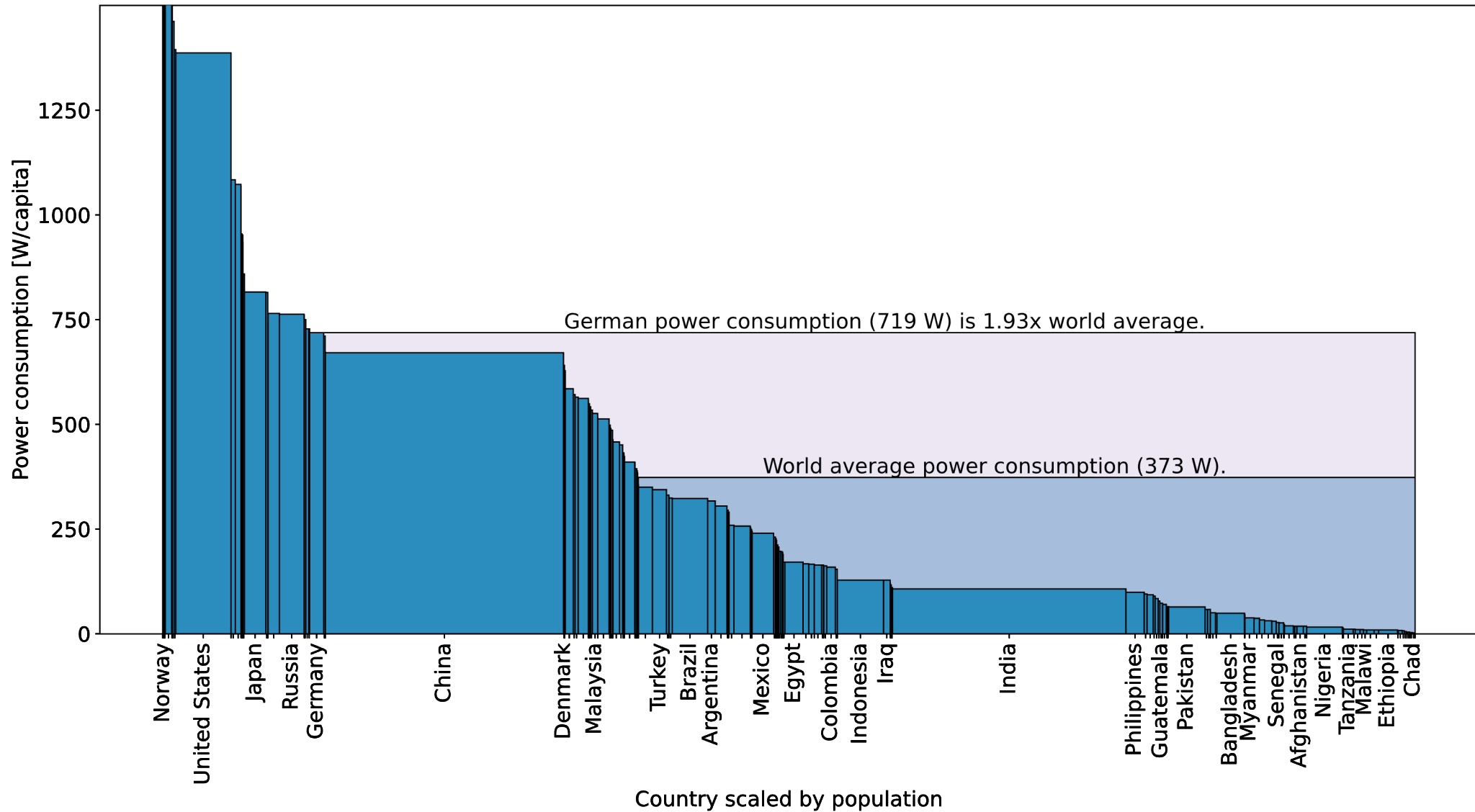
“Humans beings have never ever, lived in ecological balance with nature. It’s a myth. People have been dying in ecological balance with nature.” - **Hans Rosling**

Human Development Index vs Power Consumption



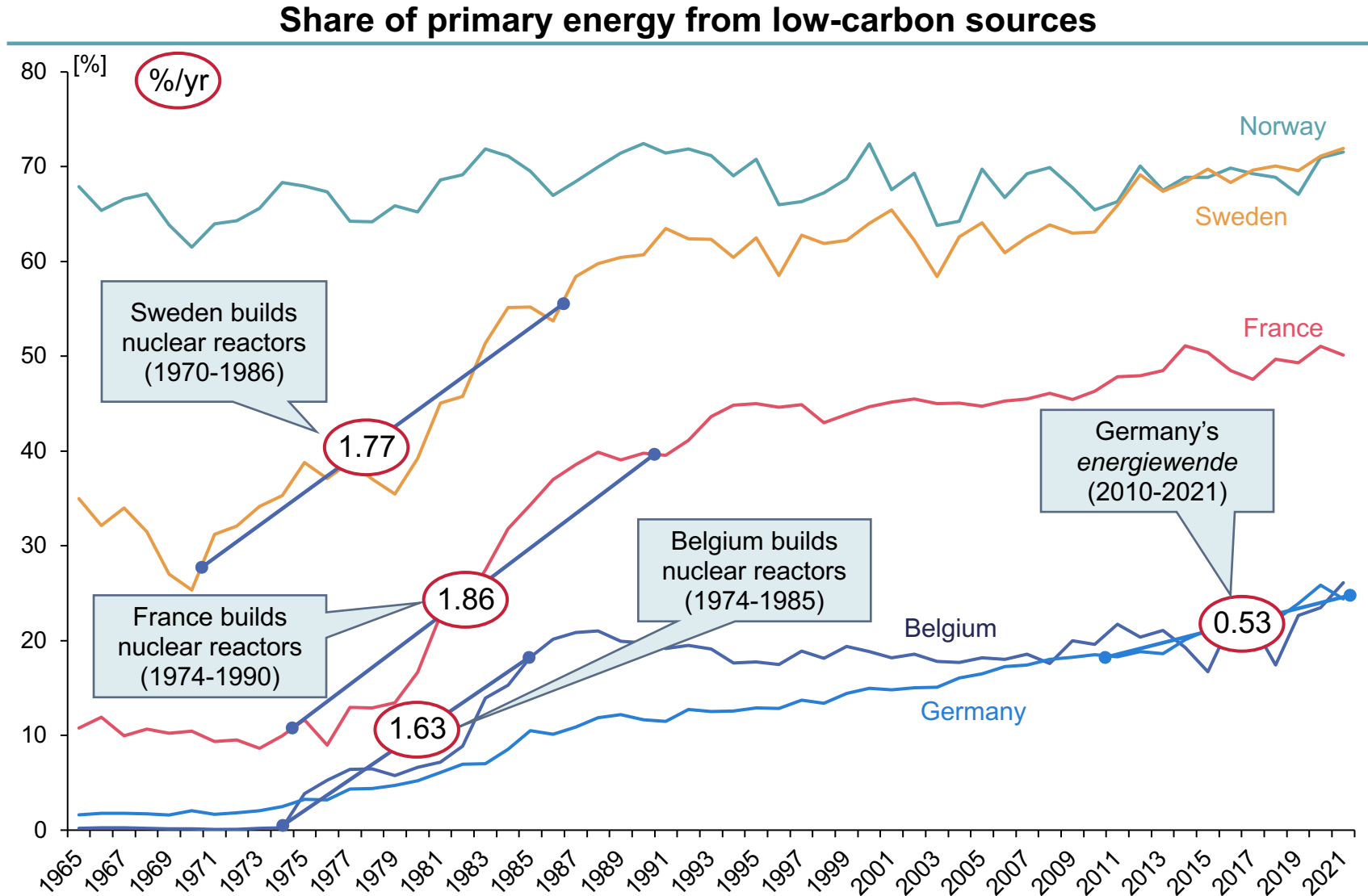
Source: ([Wikipedia.org, "Electricity consumption"](https://en.wikipedia.org/wiki/Electricity_consumption)), ([Wikipedia.org, "HDI"](https://en.wikipedia.org/wiki/Human_Development_Index))

The world needs 1.93x as much energy to lift countries up to the consumption level of Germany.



Source: ([Wikipedia.org](https://en.wikipedia.org/wiki/Electricity_consumption), "Electricity consumption")

Some of the largest low-carbon deployments have come from nuclear energy.



Source: [OurWorldinData](#), [Maarten Boudry](#)

Why did nuclear development halt?

A model used to regulate nuclear energy has some flaws..

The Linear-No-Threshold (LNT) Model

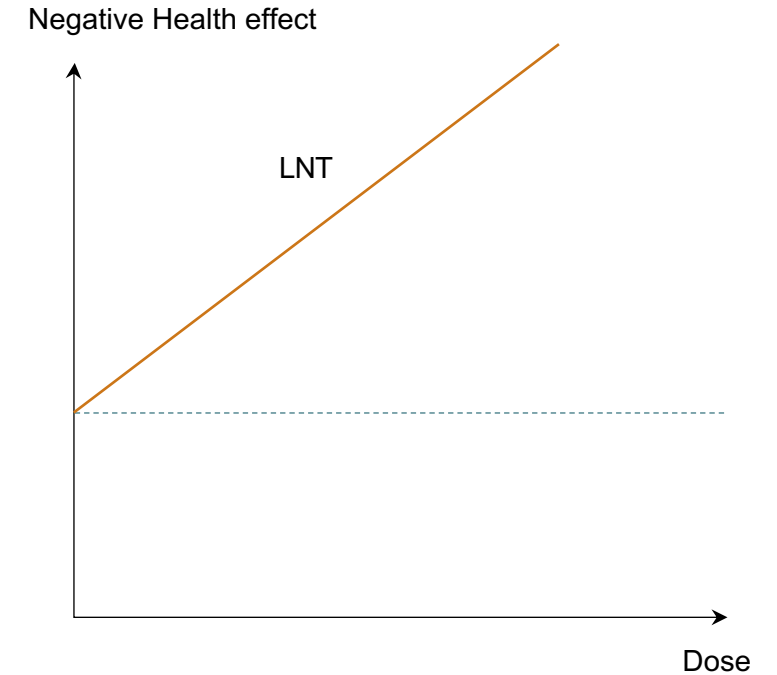
States that one extra unit of radiation provides one more unit of negative health effect.

According to the LNT model, approx. a death from radiation induced cancer happens every dose of 0.057 Sievert.



1 Banana: approx. 0.1 micro-Sievert.
148 million tons sold per year.
Accumulated radiation dose: 100 000 Sievert.
Hence, every year 5 700 people would die every year from eating bananas.

Dose-response illustration



Source: ([Henrik Berg, "LNT Examples"](#))
([Union of Concerned Scientist, "How Many Cancers Did Chernobyl Really Cause?"](#))
([Øystein Heggdal, "Hvordan kjernekraft floppet"](#))

A model used to regulate nuclear energy has some flaws..

Some examples of yearly background radiation

mSv/yr	Location
2.09	Japan
5	Norway
2.4	World
40	Kerala, India
130	Ramsar, Iran

No adverse effects
are observed

Source: ([Henrik Berg, "LNT Examples"](#))

([Union of Concerned Scientist, "How Many Cancers Did Chernobyl Really Cause?"](#))

([Øystein Heggdal, "Hvordan kjernekraft floppet"](#))

There are more and more evidence for the radiation hormesis theory, stating that some exposure to ionizing radiation is beneficial.

Radiation Hormesis

Moderate doses are beneficial, too much is not

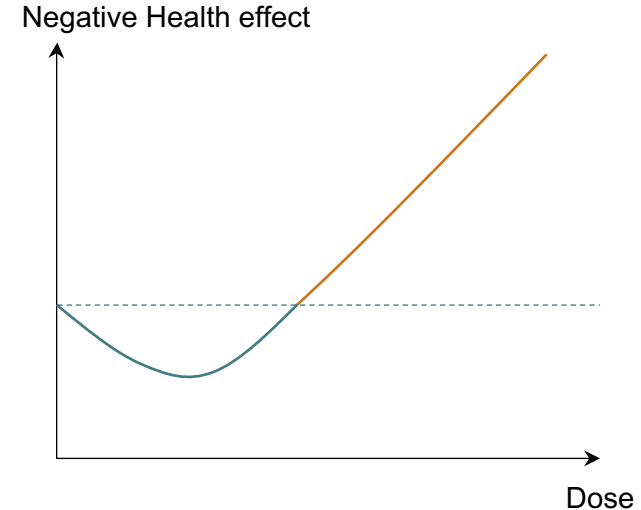
Background

Life on earth has evolved with a substantial amount of background radiation. Our bodies, and immune system, has learned to cope with this, as it has with UV radiation.

Our immune system have mechanisms to fix broken DNA strains due to ionizing radiation and other sources.

Repair hypothesis

Absence of radiation dims our immune response. On the other side, too much radiation causes more damage than our bodies can handle.



Source: ([Chatterjee, N., & Walker, G. C. \(2017\). Mechanisms of DNA damage, repair and mutagenesis. Environmental and Molecular Mutagenesis, 58\(5\), 235.](#))
([Brandt, H., Hushovd, O. T., Tellefsen, C. W., & Vigestad, Ø. \(2016\). Naturfag SF, Kap. 7 "Radioaktivitet".](#))

There are more and more evidence for the radiation hormesis theory, stating that some exposure to ionizing radiation is beneficial.

Findings	Population	Study
<ul style="list-style-type: none"> Life expectancy was approximately 2.5 years longer in people living with areas with relatively high (>180 mrem/yr) vs. low (<100 mrem/yr) background radiation. Exposure to a high background radiation displays clear beneficial health effects in humans. 	+320 million	David, E., Wolfson, M., & Fraifeld, V. E. (2021). Background radiation impacts human longevity and cancer mortality: reconsidering the linear no-threshold paradigm. <i>Biogerontology</i> 2021 22:2, 22(2), 189–195.
<ul style="list-style-type: none"> Response from low-level of radiation is non-linear, and if anything, there is a health benefit at low levels of exposure. <i>“It is a fundamental tenet of evolutionary biology that organisms [...] adapt to their environment. Hence the hormetic model also applies to oxygen, sunlight and many other familiar agents.”</i> 	NA	Higson, D. J., et. Al. (2007). Effects of Low Doses of Radiation: Joint Statement from the Following Participants at the 15 th Pacific Basin Nuclear Conference, Sessions Held in Sydney, Australia, Wednesday 18 October 2006 . <i>Dose-Response</i>, 5(4), dose-response.0.
<ul style="list-style-type: none"> <i>“Epidemiological data provide essentially no evidence for detrimental health effects below 100 mSv, and several studies suggest beneficial (hormetic) effects.”</i> Considering <i>“the high price tag (in both economic and human terms) borne by the LNT-inspired regulation, there is little doubt that the present regulatory burden should be reduced.”</i> 	NA	Vaiserman, A., Koliada, A., Zabuga, O., & Socol, Y. (2018). Health Impacts of Low-Dose Ionizing Radiation: Current Scientific Debates and Regulatory Issues. <i>Dose-Response</i>, 16(3).
<ul style="list-style-type: none"> An apartment complex in Taiwan where steel contaminated with radioactive Cobalt increased radiation dose over a period of 9-20 years <i>“They did not suffer higher incidence of cancer mortality, [...]. On the contrary, the incidence of cancers were greatly reduced”.</i> 3% less cancers and a 7% reduction of birth defects than the general public. 	~10 000	Chen, W. L., et. al. (2007). Effects of Cobalt-60 Exposure on Health of Taiwan Residents Suggest New Approach Needed in Radiation Protection. <i>Dose-Response</i>, 5(1), 63.

Impacts of LNT and the regulatory principle of As Low As Reasonably Achievable (ALARA)

How LNT and ALARA affects cost of nuclear



OPEC imposed an oil embargo in 1973, resulting in price of oil in 74 costing five times as much as in 68.



Coal got increased regulations during the 70s, with requirements on filtration and release of sulfur dioxide. Leading to increased costs of coal production.



Hence, with the ALARA principle in hand, regulations on nuclear piled up. Increasing costs to the levels of oil and coal.



Coal prices started to fall in 79 and demand for electricity stagnated in the 80s.

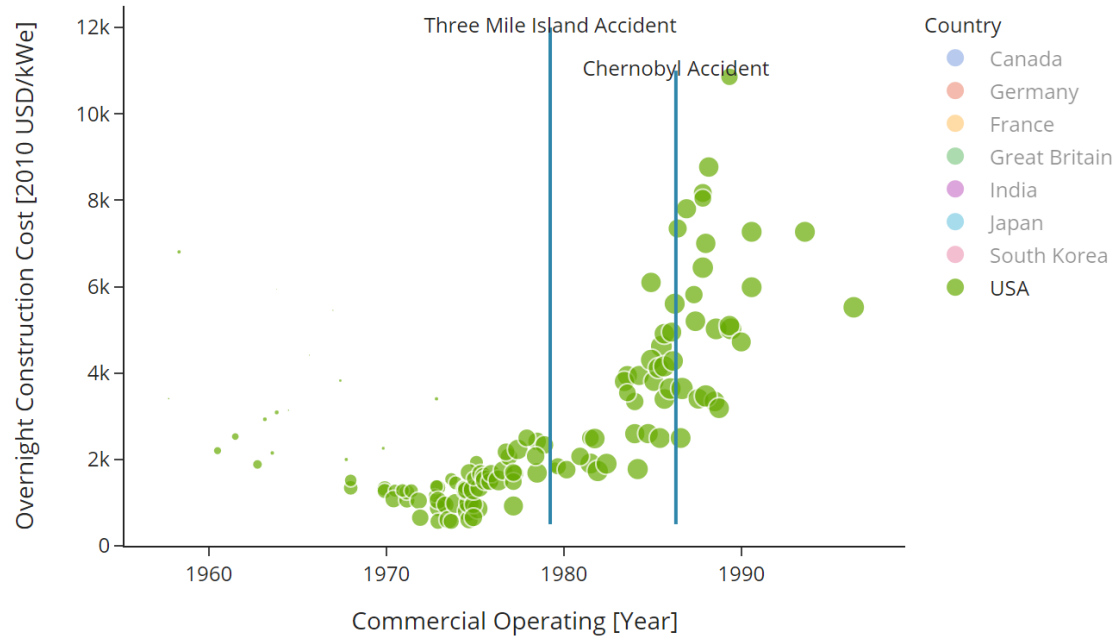
Examples from the US

- PWRs were required to handle a doubled-ended guillotine break in the primary loop.
 - A study in 1985 calculated the risk of this failure to occur **once every 900 billion years** (200x longer than the age of earth)
- In 1971 there were 100 codes and standards for nuclear power plants. In 1978 this number surpassed 1600.
- In 1978, 1.3 new regulations was imposed every day.
 - Also affecting plants under construction.
- From 1967 to 1980;
 - Construction times increased 6-fold.
 - Use of steel and concrete doubled.
 - Wiring increased almost 5-fold.

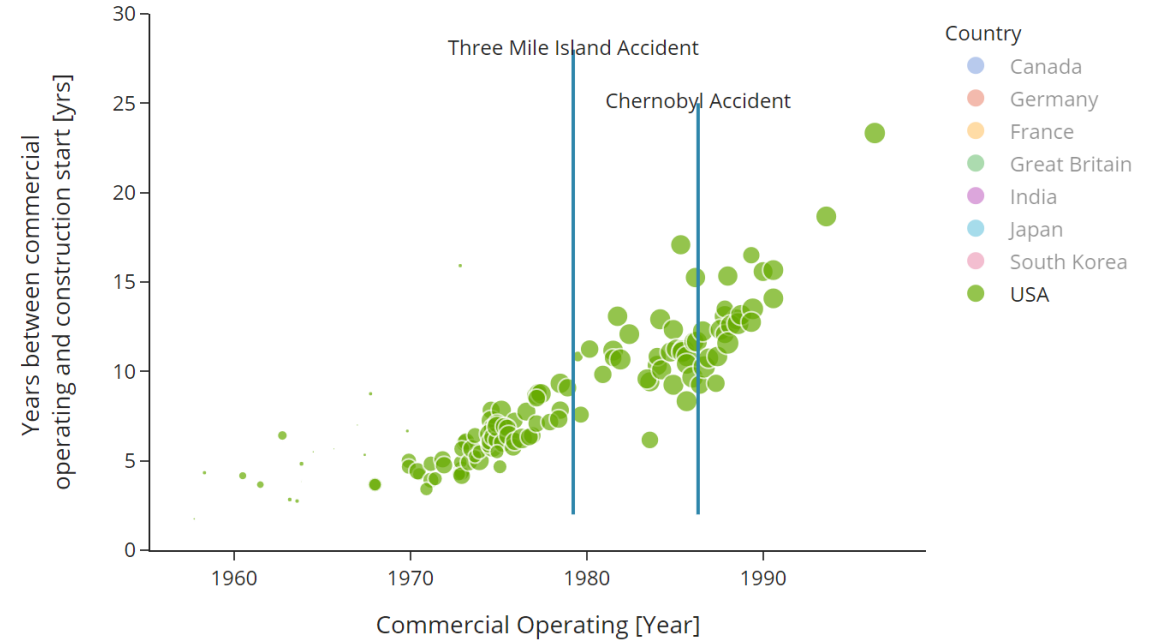
There have never been built a nuclear power plant under the current US nuclear regulatory regime (NRC established in 1974). Currently, there are only two reactors under construction in Vogtle, Georgia.

The increased costs of nuclear in the US is clearly observed in the 70's and 80's, together with increased construction times.

Overnight construction cost Construction cost less interest



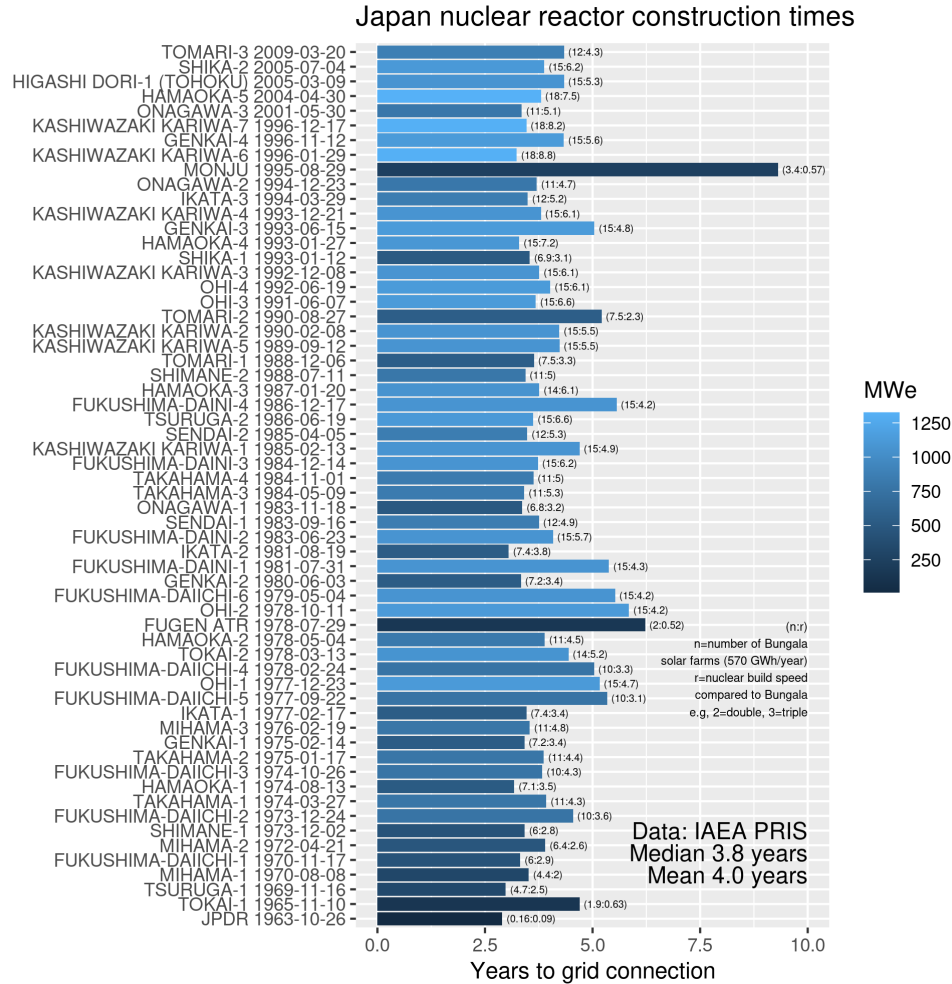
Construction time



Source: [\(Lovering, J. R., et. al. \(2016\). Historical construction costs of global nuclear power reactors. Energy Policy, 91\(April\), 371–382.\)](#)

Regulatory stability and buildout of similar plants are key to keeping costs down, as achieved by Japan.

Japan



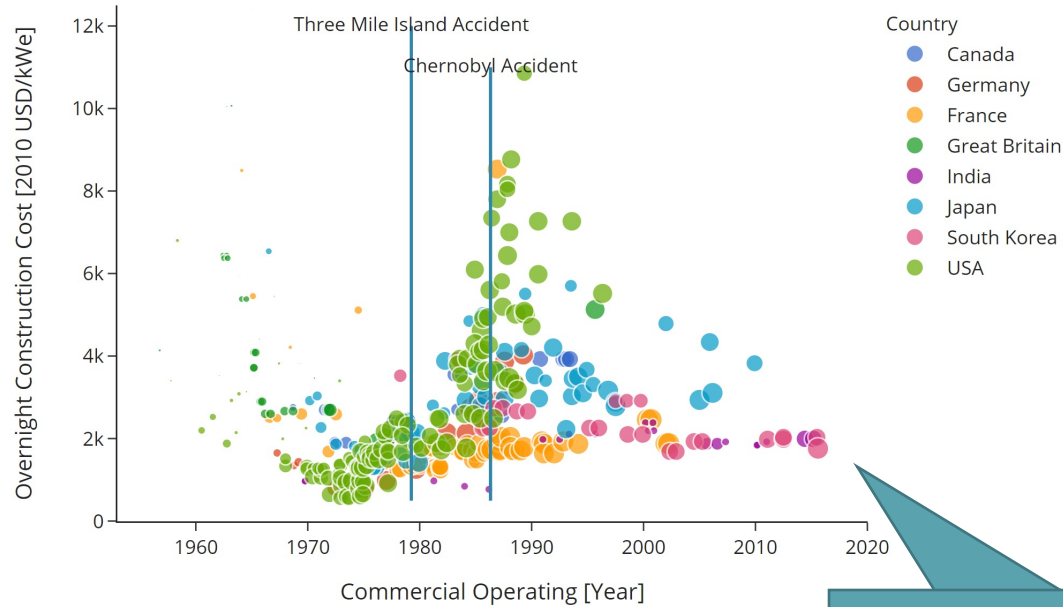
- 3.5 year construction time between 1970 and 2009.
- Shipyard-like competition
 - Mitsubishi, GE Hitachi, Toshiba

Source: ([Jack Devanney, "Nuclear Power is too Slow."](#))

1) As Low As Reasonably Achievable

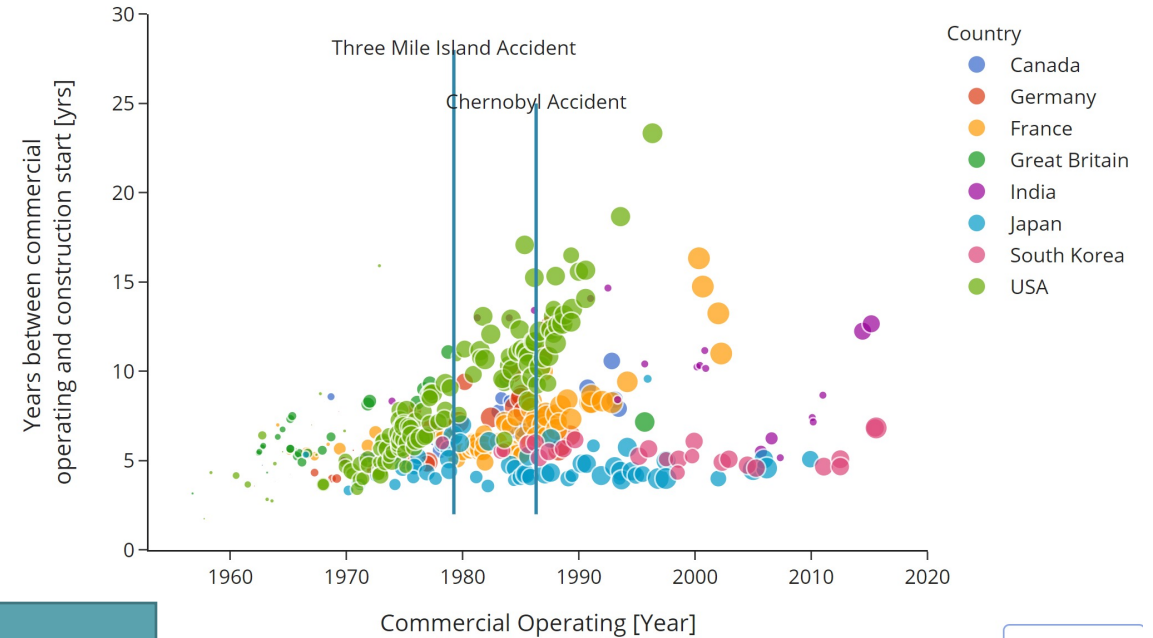
Western countries typically have a construction time of 10 years for nuclear power plants, whereas Asian countries does it in 6 years. This highly affects the costs.

Overnight construction cost Construction cost less interest



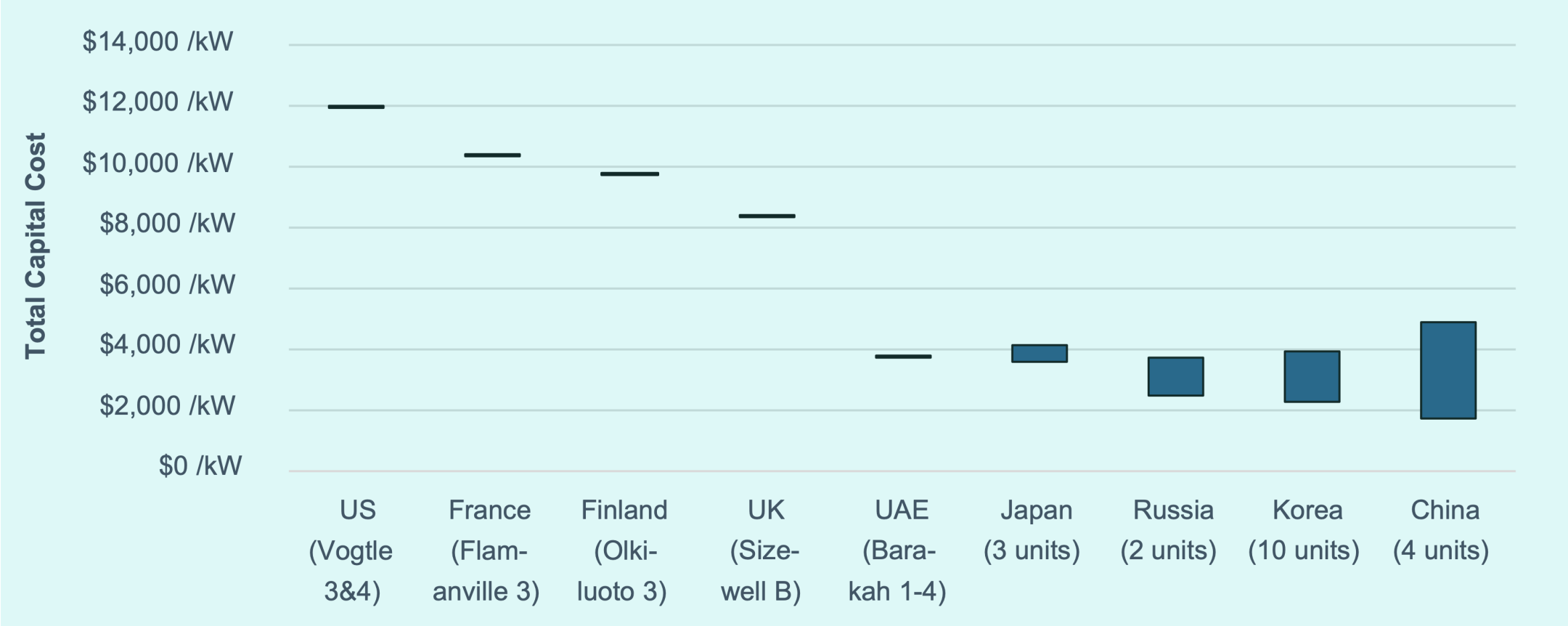
South Korea's "secret sauce"
Stable regulations, single utility overseeing construction, two and two reactors built onsite.

Construction time



Source: [\(Lovering, J. R., et. al. \(2016\). Historical construction costs of global nuclear power reactors. Energy Policy, 91\(April\), 371–382.\)](#)

Recent buildouts in the west have not been a financial success.



Kilder: [The ETI Nuclear Cost Drivers Project – Full Technical Report \(lucidcatalyst.com\)](https://www.lucidcatalyst.com), [Unlocking Reductions in the Construction Costs of Nuclear: A Practical Guide for Stakeholders \(oecd-nea.org\)](https://www.oecd-nea.org)

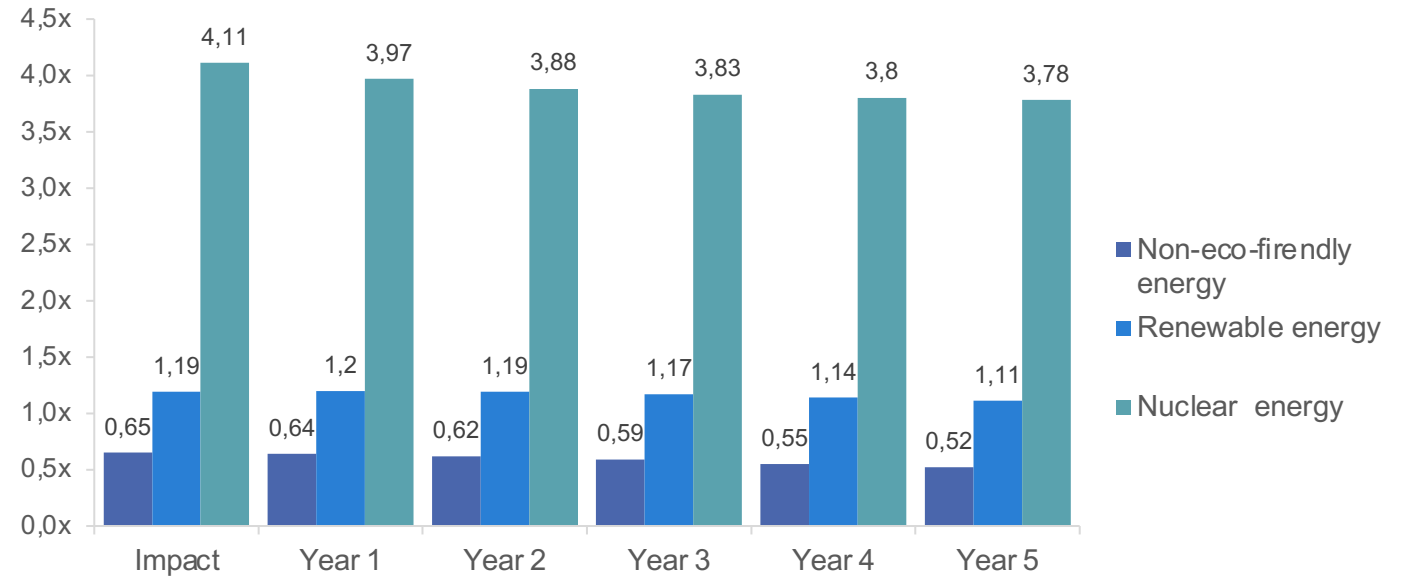
Some lesser known benefits of nuclear energy

Renewables and nuclear energy have a positive spending impact on GDP, compared to fossil (non-eco-friendly) energy, respectively 1.19x and 4.11x as an initial impact.

IMF study

- Investigates **ripple effects** from investing in energy generating technologies.
- The study concludes that investing in clean energy, like solar, wind or nuclear ends up boosting GDP more than its initial investment.

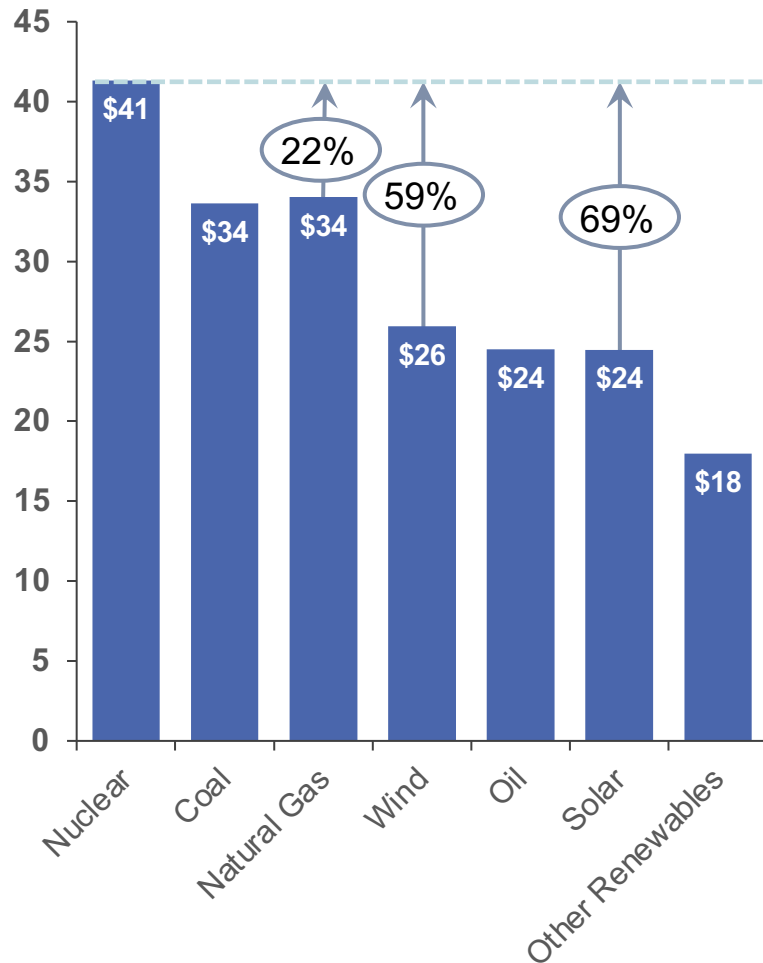
GDP impact by 1 USD spent within the different energy technologies.
[Cumulated multipliers]



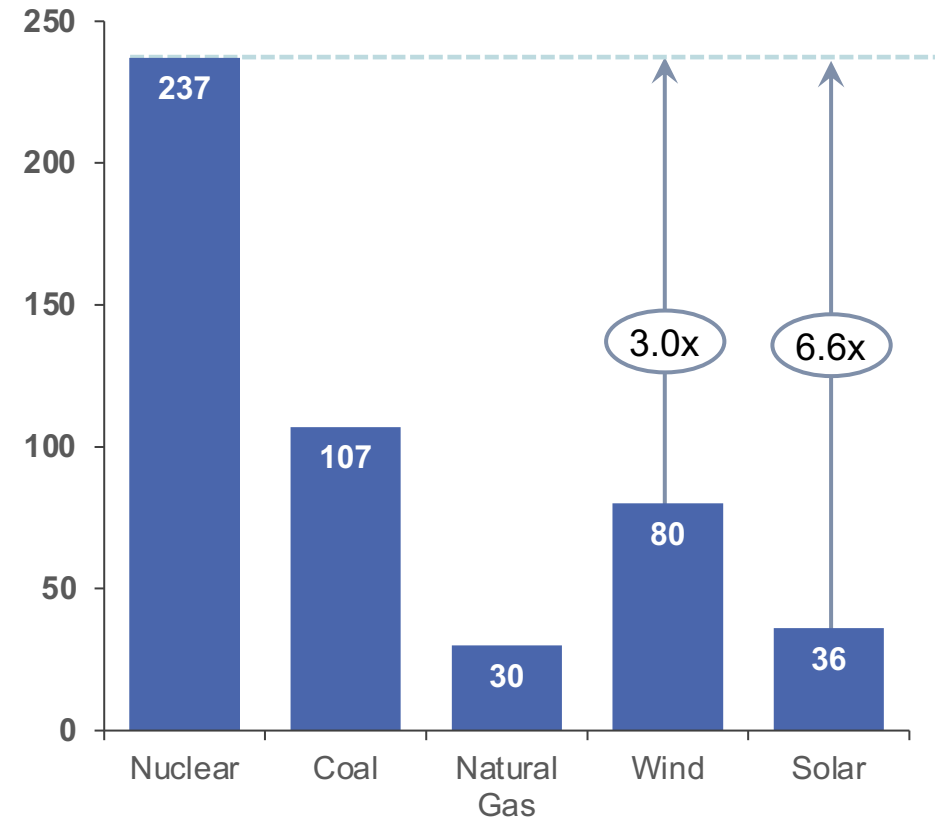
The study points out that investments in nuclear energy may lead to **larger employment of both high- and lower-skilled labor**, compared to lighter energy producing infrastructure.

Nuclear energy provides the highest paying jobs, respectively 59% and 69% more median hourly wages than wind and solar. Moreover, it provides the highest share of permanent local jobs.

**Median hourly wages by energy sub-sector
[USD]**



**Permanent jobs on site equivalent to a 1 GWe coal plant
[#]**



Source: (USEER. (2020). Wages, Benefits, and Change A Supplemental Report to the Annual U.S. Energy and Employment Report.)

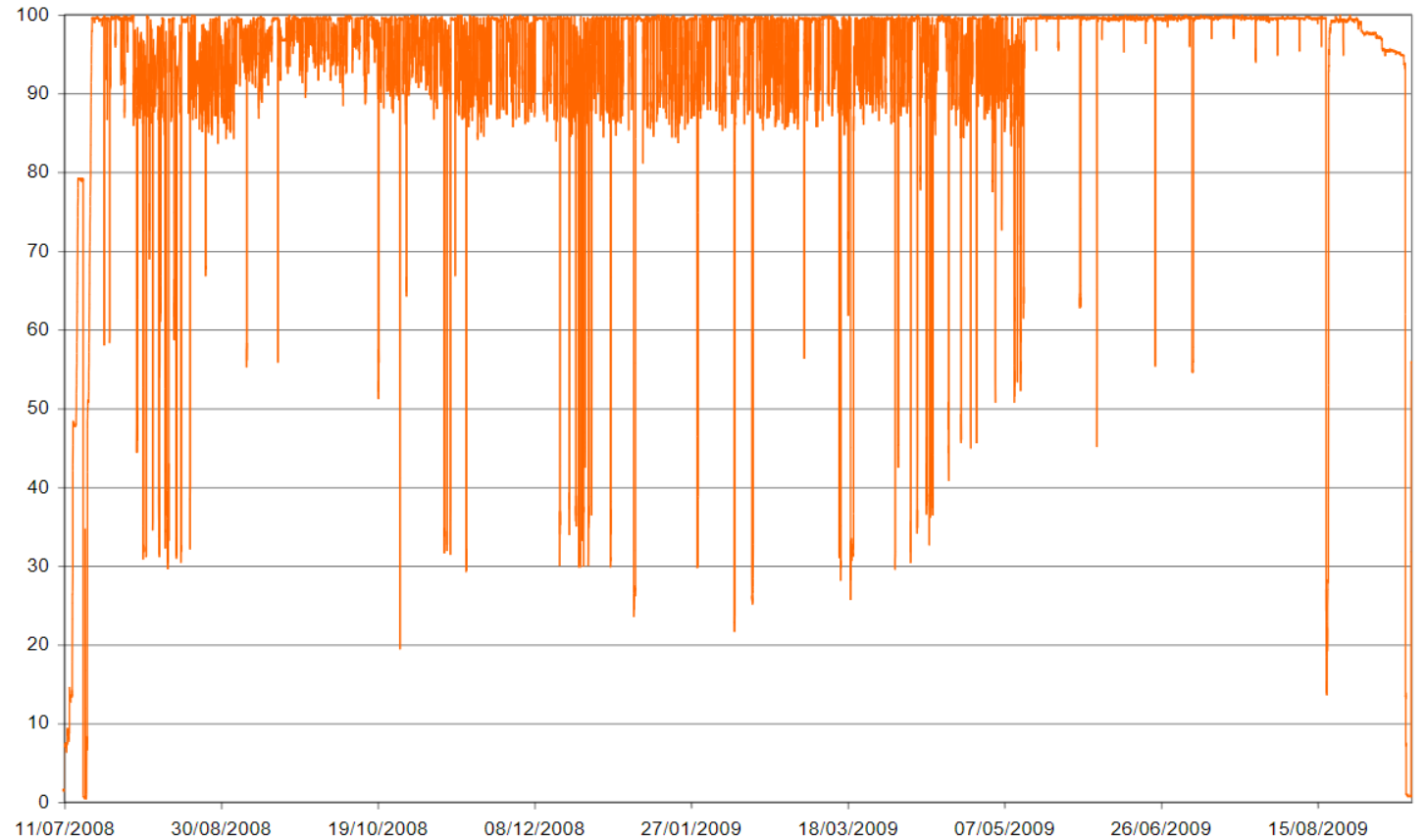
(ScottMadden Inc. (2021). Gone with the Steam How new nuclear power plants can re-energize communities when coal plants close.)

Flexibility from conventional nuclear reactors

MIT Study

We find that flexible nuclear operation lowers power system operating costs, increases reactor owner revenues, and substantially reduces curtailment of renewables.

Historic power output from a French reactor



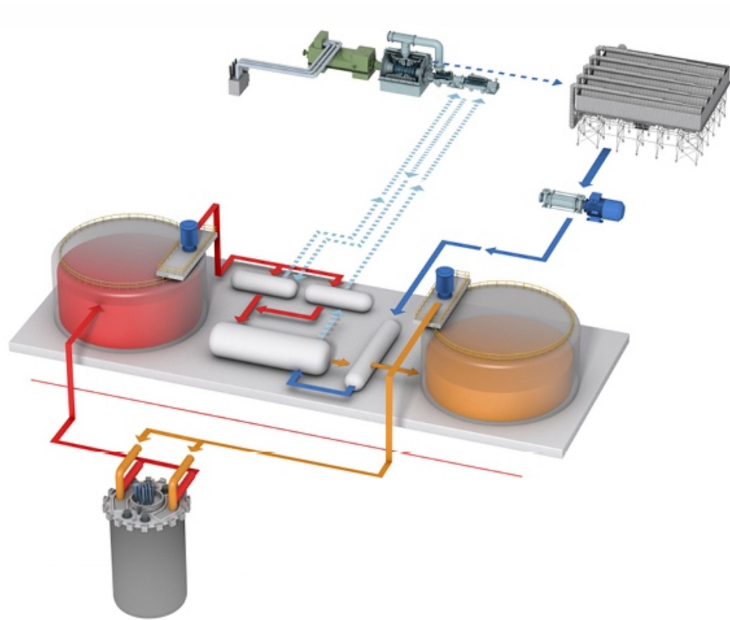
Source: [\(Jenkins, J. D., et. Al. \(2018\). The benefits of nuclear flexibility in power system operations with renewable energy. *Applied Energy*, 222, 872–884.\)](#)
[\(OECD NEA. \(2011\). *Technical and Economic Aspects of Load Following with Nuclear Power Plants*\)](#)

Advanced reactors have much more to offer in terms of flexible operation

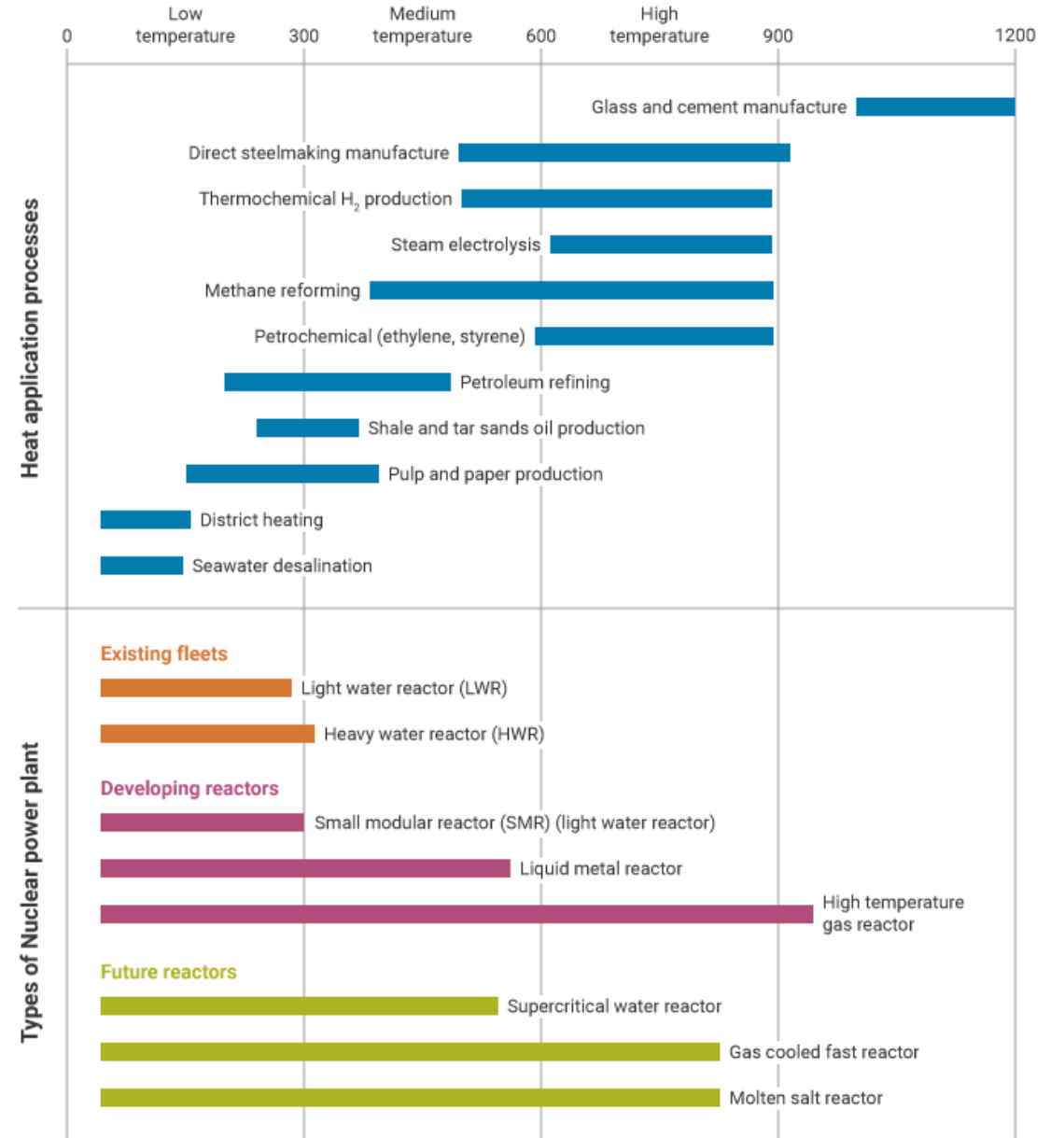
Thermal batteries

Nuclear reactors integrated with thermal energy storage

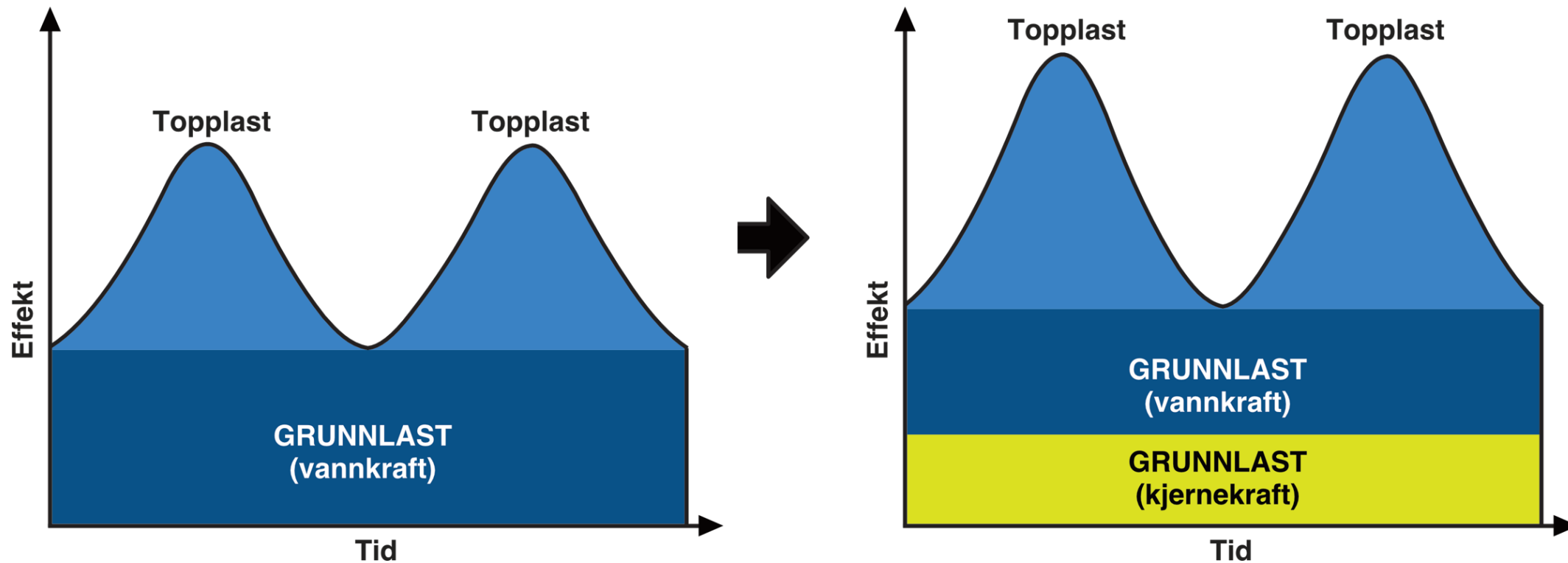
- Moltex GridReserve
 - 300 MWe baseload
 - 900 MWe for 8 hours
- Terrapower Natrium
 - 345 MWe baseload
 - 500 MWe for 5.5 hours



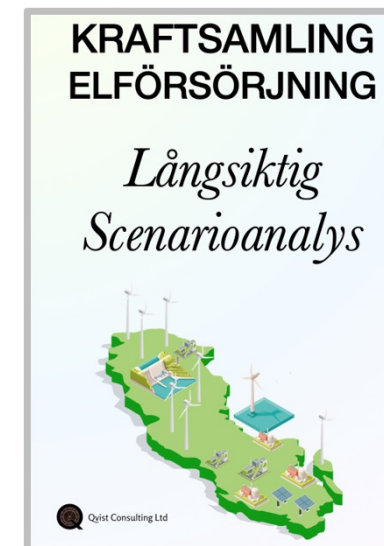
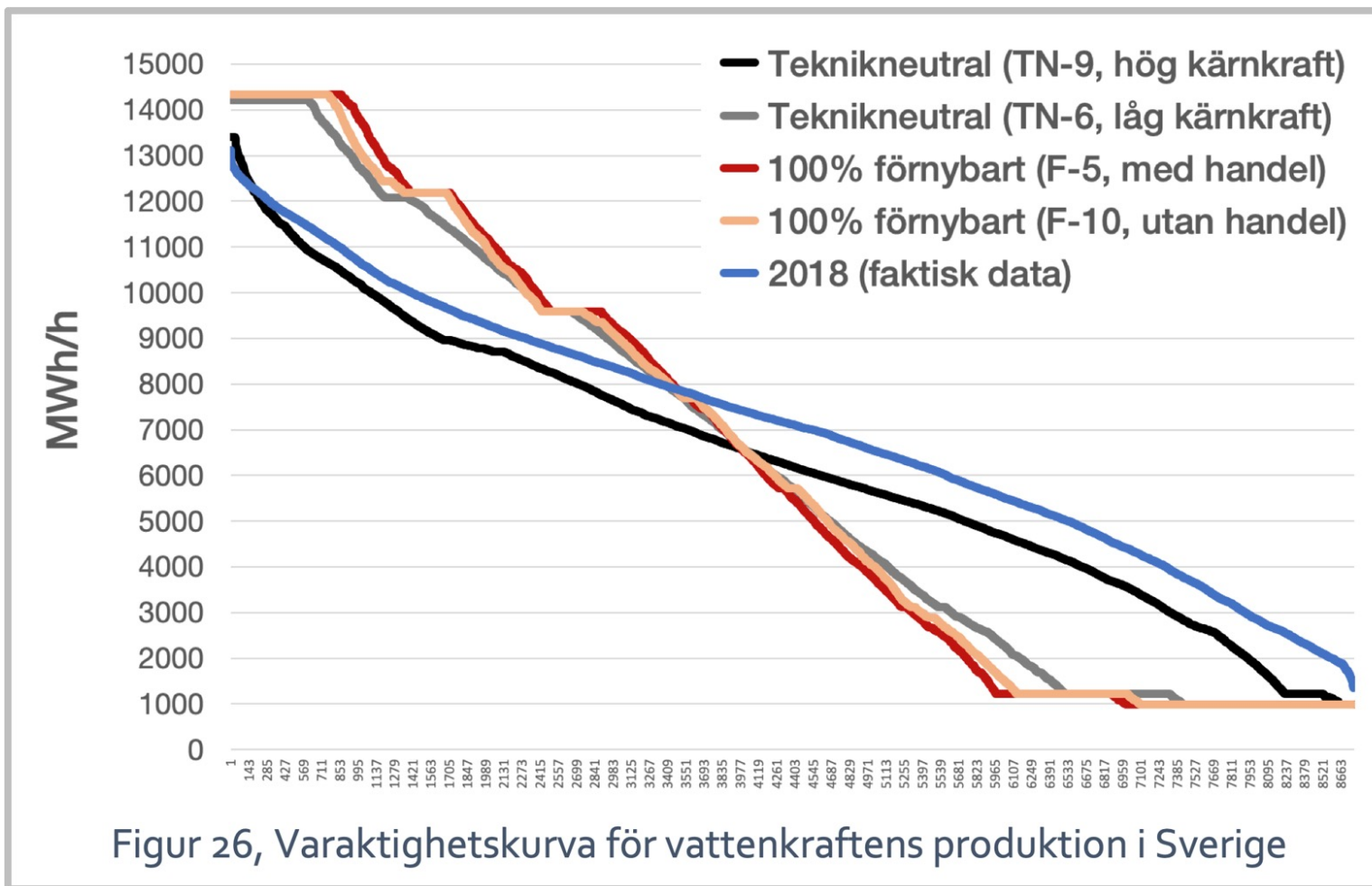
Source: ([Terrapower Natrium](#))
 ([Moltex Energy](#))
 ([World-nuclear.org, "Nuclear Process Heat for Industry"](#))



Kjernekraft kan avlaste vannkraften samtidig som den tilgjengelige effekten økes



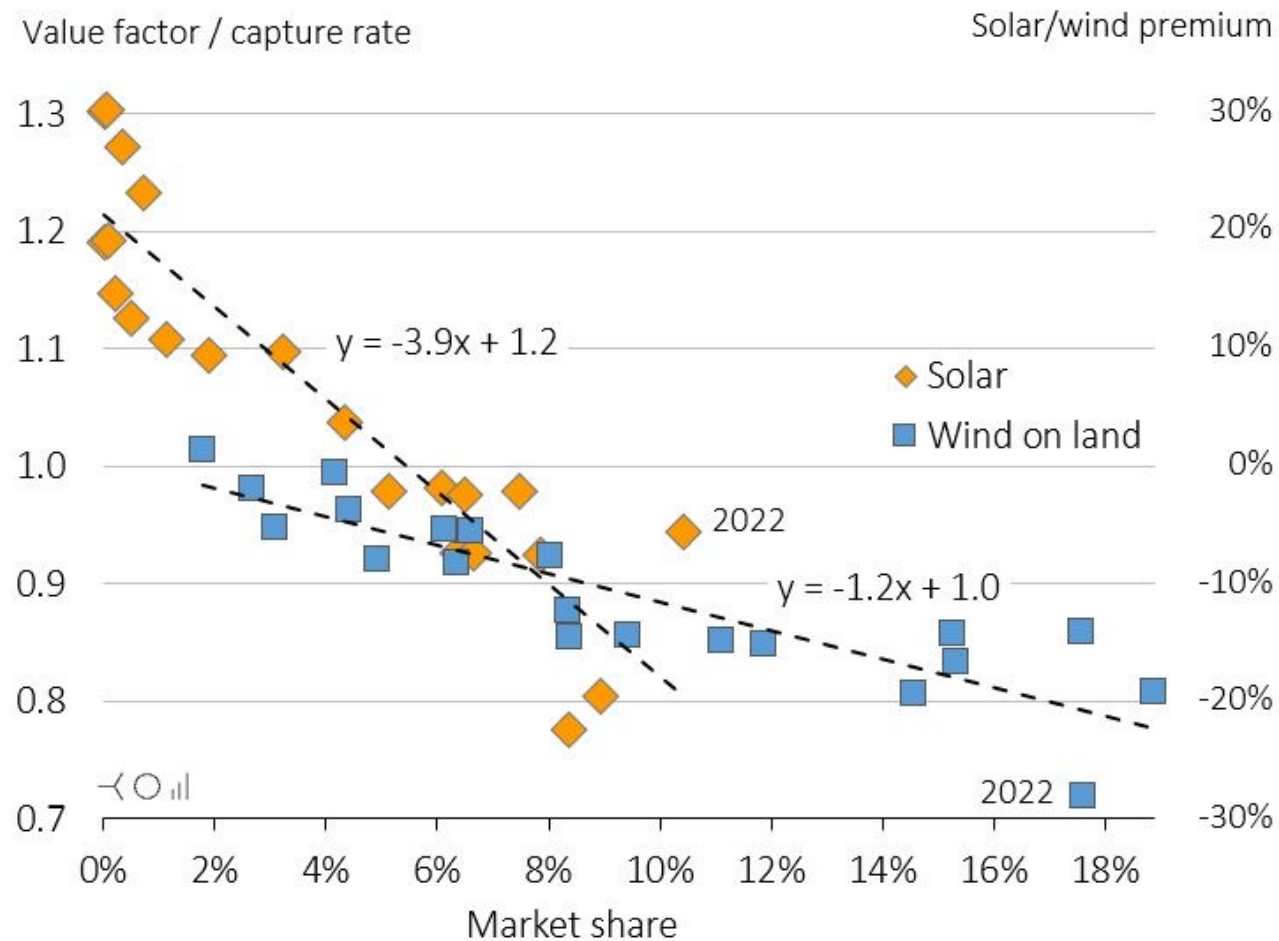
Studier fra Sverige har sett på endret driftsmønster for vannkraft for ulike scenarier



Final thoughts

Increasing shares of wind and solar reduces the value of the energy provided. Why bet everything on intermittent energy sources?

The price-cannibalism effect



Value Factor = Market value / base price. Each symbol represents one year. Updated from Hirth (2013): Market value.

- Norge har ikkje kompetanse på kjernekraft?

Good sources to learn more about (nuclear) energy

Podcast

- [Decouple](#)

Web pages

- [World Nuclear Association](#)
- [Glex Energikalkulator](#)
- [Nuclear Infrastructure Bibliography](#)
- [What is a molten salt reactor?](#)
- [Power Reactor Information System](#)
- [World Nuclear News](#)

YouTube

- [Gordonmcdowell](#)

Reports

- [Thorium som energikilde - Muligheter for Norge](#)
- [MIT - The Future of Nuclear Energy in a Carbon-Constrained World](#)

Newsletters

- [Grid Brief](#)
- [ThunderSaidEnergy](#)