The Global Renaissance of Nuclear Energy

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INTRODUCTION

In the 1960s and 1970s, many countries have seen a fast buildout of nuclear power. The fastest buildout plan was introduced by France. Within only 13 years between 1980 and 1993, nearly 300 terawatt-hours of nuclear power production were added. In the 1990s, western countries stopped developing new nuclear power plants. Oil, coal, and gas were cheap commodities and carbon dioxide emissions were no topic of importance for decision-makers. Nuclear energy was too capital intense in comparison to fossil fuel-driven power stations. New political "green" movements emanated, that fought nuclear power, often funded by fossil fuel interests. The nuclear accident of Chornobyl, although technically impossible in all Western power stations, added to the erroneous fears that nuclear power could not be controlled sufficiently

The communication style of the nuclear industry in Western countries – essentially focusing on technical information for engineers, but ignoring the emotional side of the technology – created a void that greenish non-government organizations were happy to fill.

Since the beginning of the 2020s, a global energy crisis started to evolve. Most of the reasons were policy-driven.

Weather-dependent power sources, that had become dominant in several large countries, were underperforming in the first half of 2021 due to unexpected weather. In Brazil, hydropower fell short of expectations, and in several European countries, wind energy. Unfortunately, these power sources had been built out without a proper, systematic analysis of the risks associated with increasing dependency on wind and solar irradiation in power production.
To replace the energy, natural gas was used to produce electrical power, creating an unexpected increase in demand.

The supply of natural gas and crude oil could not be ramped up fast enough. The 'divestment' movement from political activists and capital market participants had reduced the amount of capital for funding fossil fuel production despite an unchanged global 80 % dependency on fossil fuels. This situation is going to impede the upstream industry for some years.

As a result, the prices for fossil fuels have multiplied within the calendar year 2021. The Russian assault on Ukraine has aggravated the scarcity of energy supplies further.

In this light, many countries are considering or reconsidering nuclear energy as a stable, reliable, and relatively cheap source of energy, both for electricity and for industrial heat. As a relatively new trend, some countries foster the development of small and modular reactors (SMR). Around 70 companies globally are developing "new nuclear", hence traditional pressurized water reactor (PWR) technologies and molten salt reactors (MSR) initially developed in the 1950s, or outright new designs that combine inherent safety with low production costs, such as Oklo, Copenhagen Atomics, or Dual Fluid Energy.

This article outlines some trends in the global nuclear industry and argues that they have the potential to initiate a renaissance of nuclear power globally. We describe technological trends from an economic perspective and discuss their social and political implications as enablers for a transition from a world with some 450 nuclear power stations to one with ten thousands by mid-century.

TECHNOLOGICAL TRENDS IN NUCLEAR ENERGY

The past: Existing nuclear fleet is still in excellent condition

Nuclear power plants were developed in the 1950s and 60s. Their technical maturity was reached in the 1970s and 80s, and hundreds of power plants were built in many countries. The accidents of Three Mile Island, Chornobyl, and Fukushima triggered a vivid debate in the public on nuclear safety. In response, the nuclear industry created a global network that dealt with the technical and organizational root causes for these failures. Close to all nuclear power plants in operations globally have implemented safety features that would have prevented the accidents.

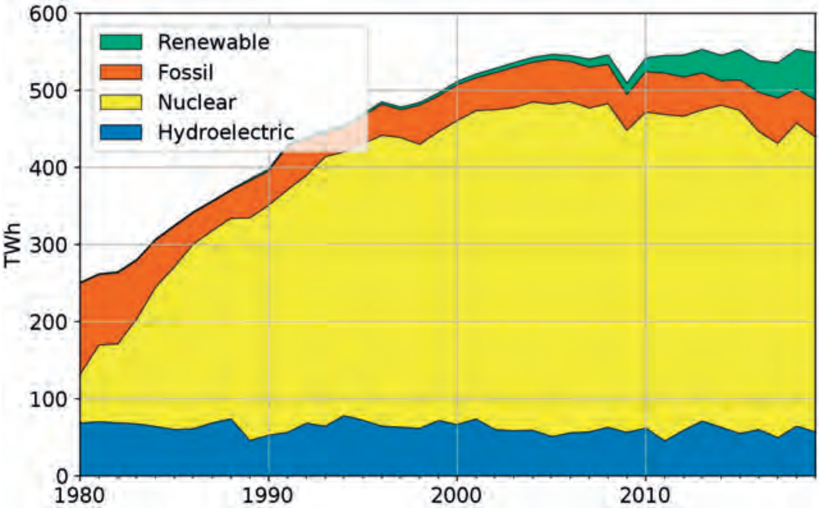

Fig. 1:
Electricity production in France by Theanphibian - own work, public domain, https://commons.wikimedia.org/w/index.php?curid=10123493

These safety features include not only technical improvements but organizational measures, which acknowledge that any power plant is a socio-technical system, where technology communicates with humans, not only the other way round.

As a consequence, nuclear power plants (NPP) are different engines and organizations today as compared to the time when they were built. Policies permitting, they could have a long-lasting future ahead of them. It is hence a positive sign that the premature closure of fully functioning NPPs is less and less accepted, e. g., in California, Belgium, and Germany, by the electorate.

The present: Generation III+ reactors

All large-scale, new-build reactors are Generation III+ reactors. These are defined as reactors that are able to contain the consequences of a meltdown to the reactor itself; a meltdown is still possible under extremely rare conditions and might destroy the power plant without harming the environment. In the case of Russian, Chinese and Korean models, their Generation III+ reactors are efficient, safe, affordable, and are usually built within 5–8 years. In contrast, French and US-American projects are characterized by long

Fig.: 2:
Nuclear Power Plant Olkiluoto, Finland OL3 von Kuusisenmaa aus: Tapani Karjanlahti / TVO

delays and substantial cost overruns. Quite obviously, the disruption in the development and construction of nuclear power plants in Western countries, as described above, caused an entire generation of nuclear engineers to change jobs or reach retirement age. After such long delays without active projects, the practical knowledge on how to develop and build nuclear power stations has gotten lost. Nonetheless, countries such as Poland and Turkey are considering, among other technologies, investing in Generation III+ models from the U.S.A., France or Korea. France has announced to build at least six new reactors.

In countries with substantially lower power consumption than the leading OECD countries, such as Estonia and many African countries, Gen III+ reactors are often oversized. There, SMRs are preferred over large-scale reactors as long as they are cost-effective.

The future: SMR and large reactors, for power and heat production

A relatively new trend is the emergence of Small Modular Reactors (SMR). This concept is offsetting a decade-long trend to create bigger and bigger reactors, hence exploiting 'economies of scale.' The basic concept here is that doubling any engine's capacity does not increase its cost by a factor of two, but – depending on its component – typically between the square root to the cubic root of two. Over the decades, the net electrical capacity of nuclear power plants has increased from a few hundred megawatts to 1.60 gigawatts in the case of Finland's Olkiluoto-3, the latest addition.

The concept of small offsets this development, while it has always been the goal of nuclear power plant manufacturers to standardize their production processes as much as possible (see below).

So, what exactly does *small* and *modular* mean?

'Small' has been defined as an electrical capacity up to an arbitrary threshold of 300 megawatts. Several dozens of projects exist that develop reactors within this capacity. The main advantage of smaller reactors, potentially offsetting missing economies of scale, is supposed to be safety-induced savings: If SMR designs do not need external cooling to shut down safely, which is often referred to as 'walk-away safety', active cooling systems along with their controls are not required. The cost-saving of not needing so many safety components is substantial in the developing, licensing, building, operating, and decommissioning phases.

It should be noted that an important part of the licensing process is to study the interaction between the different reactor components and safety systems. The development of safety scenarios is hence in parts a combinatory problem. Fewer systems allow for far fewer interactions, thus substantially less effort in designing, constructing, and licensing the entire NPP.

'Modular' means, in analogy to prefabricated houses, that many components – even the reactor core itself – can be produced as a whole in the protected environment of a factory, and then the reactor is shipped in whole to the construction site.
Economies of scale are implemented hence not by large size but by a high number of reactors sold. As each reactor is identical to the others of a series, this significantly reduces manufacturing costs and increases quality. In an analogy to the aircraft market, the new NPP will be closer to airplanes than to airports. Thus most SMR models will have the potential to operate at a higher reliability and lower cost than large tailored PWR models.

Further, approval processes follow international standards but are of national responsibility. National nuclear supervision authorities cooperate across the globe. If an SMR is approved in one country, the others, almost identical, will follow suit, speeding up approval processes and saving costs.

Some SMR developers plan to radically reduce fuel costs because they can burn natural uranium, thorium, plutonium, or "nuclear waste" completely. In the latter case, there would even be a negative fuel cost. In some models, fuel lasts 6 to 25 years, reducing refueling times. As some of these SMR models will be breeder reactors, the range of fissile material would be stretched by a factor of around 100, and as there are billions of tons of Uranium and Thorium in the oceans, nuclear fuel would be a truly sustainable resource, lasting for several hundred million years at current consumption rates, if all energy mankind uses came from nuclear energy.

The safety and sustainability features of nuclear energy make them compliant with ESG (environmental, social, government) regulations, such as the EU Taxonomy, thus reducing capital and insurance costs of nuclear investments, as soon as financial market players price them in.

Further, these safety improvements, due to the SMR's inherent lack of hazard, might be used to justify a substantial reduction of regulatory requirements, and abandonment of unique and burdensome "nuclear grade" quality assurance requirements. This is a more fundamental change than merely reducing the number of safety components. Given the loss of economy of scale, such a reform might be the most important lever to make SMRs competitive.

With such design changes, the electricity sector could be transformed substantially. But what about all other sectors where we use energy? Even in developed countries, electricity is less than a quarter of total primary energy usage. The remainder is used for heating, mobility, process heat in the industry, and material use of energy commodities.

Hence, new and safer reactor models would open up the space for cogeneration of power and heat. Excess heat could be used for the desalination of seawater on a large scale. Those reactor models that produce high temperatures at or above 500 °C could fuel chemical reactions for mass hydrogen or synfuel production. At 800 °C or more, the production of steel, glass, cement, and base chemicals independent of fossil fuels could be enabled. The associated economies of scope will boost demand, as none of the weather-dependent sources of energy will be able to compete even close in quality and efficiency to the heat sources nuclear energy can provide.

Hydrogen production by way of chemical reactions, instead of a detour via electricity and electrolysis of water, has substantial benefits on the cost side. To produce power from heat, then to use the power to create hydrogen or synfuels that are mainly characterized by their calorific value, wastes a large part of the initial heat energy. The direct usage of this heat for fuelling chemical processes would cut out these heat losses and make hydrogen/synfuel production substantially cheaper, to a level where it can compete with fossil fuels.

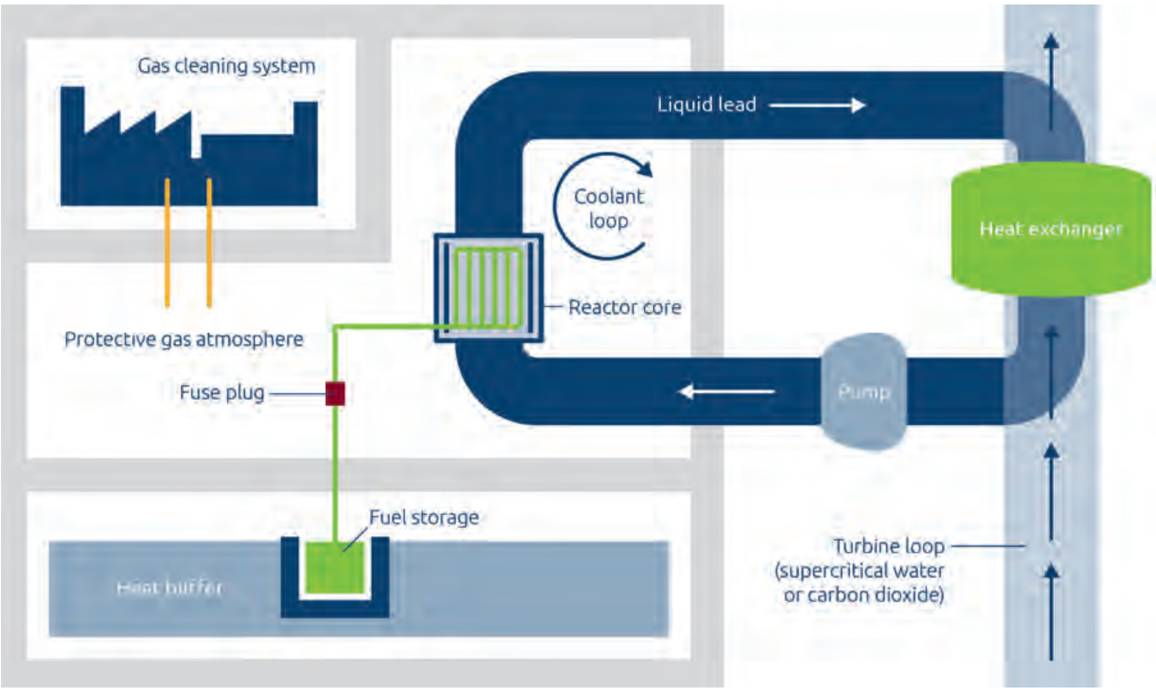

Fig. 3:
Dual Fluid modular power plant DF300 (300 MWel). The fuel is delivered to the power station in a sealed cartridge. It is then heated and pumped into the reactor core, generating heat for about 25 years. At the end of the burning cycle, the spent fuel is transported to a recycling facility.

SUCCESS FACTORS WITHIN THE NUCLEAR INDUSTRY

If the nuclear industry wants to live through a renaissance, it has to transform its operating procedures and its conditions in the social process. Those nuclear plant producers that meet these conditions will profit more successfully from the evolving market of 150 to 200 GW globally per year by mid-century. Part of this demand is the replacement of current power stations but a larger part will be additional power and heat demand, mainly in the growing economies of Africa and Asia.

Large reactors in large grids

Power stations, in particular large power stations, require large, developed grids to operate in. Wherever this infrastructure is in place, the manufacturers of large pressurized water reactors will be able to pick up market demand, as long as they master the production process and have proven in time and budget deployment of nuclear energy. For large-scale PWR,

Fig. 4:
Nuclear Power Plant Cruas, France.

it will therefore be crucial to study carefully the conditions that made them successful in the 1970s and 1980s and then try to imitate those conditions.

A good example of efficient reactor deployment is the construction of the German Convoi series. In the decades before, students of nuclear engineering had profited from a high reputation among their peers, and excellent talent was attracted to the industry. Policymakers decided to commission many reactors of similar type within little time. Financing was mostly done with private capital but in the same cases with state guarantees. The construction teams were gathering every quarter or so across all companies involved, and with their best-skilled individuals, to discuss what went well and where they could jointly improve.

As a result, every reactor was built faster, cheaper, and at higher quality standards than its predecessor. German reactors scored highest in the global availability ranking. In some years of the 1990s, seven and more out of the global top ten most reliable NPPs were German. German electricity prices, in contrast, were among the lowest of industrialized nations.

Unfortunately, the U.S. and France have forgotten how to build large nuclear reactors efficiently, and Germany has forgotten to do so completely. It is a good sign that several countries, such as France, the UK, and Poland have issued build programs for large-scale reactors, where a handful of reactors are going to be commissioned in the next years. To recruit a sufficiently high number of nuclear engineers, the perception of nuclear engineering needs to be influenced among young people.

Nuclear energy needs to be cheaper than fossil fuels

From a broader perspective, we are living through a productivity crisis very similar to the era at the end of the 18th century. At the time, the medieval farming methods had come to an optimum, while the population was growing rapidly. Thomas Malthus postulated in 1799 that if the population grows exponentially and agricultural productivity only linearly, a hunger crisis was immediately to follow.

This perspective did not take technical progress into account. The invention of chemical fertilizers, tractors, pesticides, cooling technologies, and so on multiplied food production per unit of surface. Today, more people suffer from obesity than from hunger. The optimization of fossil fuel usage and the abundance of cheap energy spur simultaneous population and prosperity growth at an unprecedented level.

Nonetheless, similar prophets to Thomas Malthus arose in the late 20th century. Fearful of natural energy resource exploration and production being slower than population growth, they demanded a turn away from fossil fuels toward weather-dependent sources of energy.

Today, this strategy proves to be costly: All countries that have invested heavily in solar and wind energy suffer from energy scarcity and high power prices. It is here where nuclear energy might be able to be seen as a remedy. If it is substantially more affordable than power systems with intermittent sources, and at par with fossil fuel usage in power system cost, fuels, residential heating, and industrial heat provision, then more and more nations in developed and developing countries will turn to nuclear energy. The break-even price points can easily be derived from long-term (before-crisis) energy costs:

- Power systems are dominated by coal. 80 USD/mt – so far the cheapest form of electricity – define a price point of 4 cents/kWh that has to be met by nuclear power.
- Heating energy at around 6 USD/MMBtu for gas corresponds to 2 cents/kWh for synthetic heating gases (syngases), such as hydrogen or methane, produced by high-temperature nuclear reactors.
- To match 50 USD/bbl crude oil, synthetic fuels should cost no more than 3 cents/kWh or 33 cents/liter.

If prices for power, syngases, and synfuels from nuclear energy could be reduced to these price points, even those countries that are not compliant with CO_2 reduction policies may adopt nuclear energy. Further strong arguments for nuclear energy as a source of power, syngases, and synfuels are ease of handling based on the same systems as before (e. g., combustion engines), negligible air pollution, and low land consumption. On the other side, the operation of nuclear energy plants requires different skills than traditional fossil fuel value chains. There are hence still some investments required.

However, this is no different from large-scale deployment of technologies that use solar and wind energy to produce power and syngases.

Energy systems predominantly based on solar and wind energy will find it extremely hard to meet the price points of fossil fuels. Governments who impose such technologies on their citizens at any cost will weaken their economies. The idea that energy consumption should be expensive is flawed in itself, and arguably even dangerous.

Too much of a politically induced financial burden on energy usage will absorb the funds necessary to afford the transition to better alternatives, if and when they are developed to maturity. But the danger goes further to the social contract itself. The global economic crisis enrolling 2008 was triggered by crude oil at 140+ USD/bbl. The poorest third of the US population paid too much for fuel and couldn't pay their mortgage. The USA reacted wisely with an energy turnaround from importer to exporter of fossil fuels.

In Europe, there is no such option. Social unrest similar to the yellow vest protests in France and the dissolution of society will inevitably evolve, in particular, once people understand that high energy costs and their misery were intended by a misled elite. Policies that suggest "if you don't have bread, eat cake" have cost quite some heads in history.

We won't be able to decarbonize the global economy if we don't combine it with human welfare and prosperity. Nuclear energy has this development potential, but the industry must find a way to make nuclear energy affordable by adhering to a strict design-to-cost approach, to make it easy and to make it safe. Economies of scale, modularization, simplification, education, and better explanation are key to making nuclear energy the key energy technology in the 21st century.

CONCLUSION

The nuclear industry has been under pressure in the past thirty years, due to cheap oil and gas, as well as anti-nuclear lobby groups, whose false claims the industry was not capable of countering adequately. We are now at a turning point. The nuclear sector is currently one of the most innovative ones. The 2020s will mark strong technical progress in both the existing and the advanced sectors. The 2030s will mark their technical maturity, with many new nuclear companies reaching series production at high output, providing power, process heat, and synfuels to many in many economies. The future of nuclear energy has yet to begin properly.

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