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CONTENT

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SMALL MODULAR NUCLEAR REACTORS – NEW PERSPECTIVES IN ENERGY TRANSITION

VASKO GERASIMOVSKI AND VLATKO CHINGOSKI

Abstract. Nuclear power has been declining in importance over the last quarter century, with its share of global electrical energy generation decreasing from 17.5% in 1996 to around 10% in 2019, mostly over gas-fired power plants and recently renewable energy sources. Small modular and advanced nuclear reactors (SMR) have been proposed as a potential way of dealing with the problem, such as specifically economic competitiveness, risk of accidents, link to proliferation and production of waste, confronting nuclear power technology.

This perspective paper examines whether these new designs can indeed solve these problems, with a particular focus on the economic and global climate challenges. It briefly discusses the technical challenges confronting advanced reactor designs and the many decades it might take for these to be commercialized, if ever, as a result of the slow-paced development of appropriate legislative. Next, it examines the potential savings from their light and modular construction, and explains why the historical record suggests that these savings could be adequate to compensate for the economic challenges resulting from the lower generation capacity. It then critically examines arguments offered by advocates of these technologies to justify subsidizing and constructing these kinds of nuclear plants with respect to job creation and other potential uses of electricity generated in combination with heat providing balancing mechanism for emerging installation of renewable energy sources. It concludes with an assessment of the markets for these technologies in the coming decade.

1. Introduction

The global threat of climate change is making the need for clean energy more urgent than ever. In the race to reach net-zero emissions and reduce reliance on fossil fuels, nuclear power is gaining increasing support [1]. Additionally, Russia's invasion of Ukraine has had a seismic effect on global energy prices, driving up energy costs for consumers and businesses alike. In Europe, the annual energy bills are at the highest level for the last 50 years and rising [2]. According to the International Energy Association (IEA), the high price of energy risks hampers efforts to reach current climate change targets, and the world is already behind on meeting its commitments. Much more investment in clean energy technologies is needed if the worst effects of unchecked global heating are to be tackled in time.

Although in some countries nuclear energy is considered a renewable energy, for example in the UK, in general nuclear energy could not be treated as pure renewable but rather as recyclable energy. According to the UK's Nuclear Advanced Manufacturing Research Centre, while the usage of nuclear energy does raise several dubious issues such as investment cost, waste management and safety, in terms of greenhouse gas emissions per unit of power produced, it is as clean as offshore wind, thus makes it one of the lowest carbon emission energy sources [3], [4].

Date: October, 2022.
Keywords. Nuclear power, Nuclear reactors, Small modular reactors, Renewables, Energy generation.

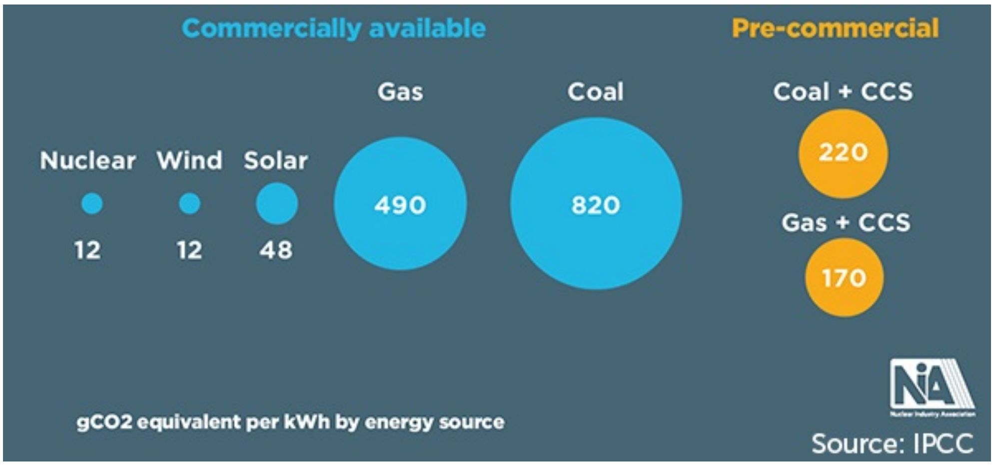


Figure 1: *Carbon footprint of some energy sources*

2. Theoretical background of SMRs

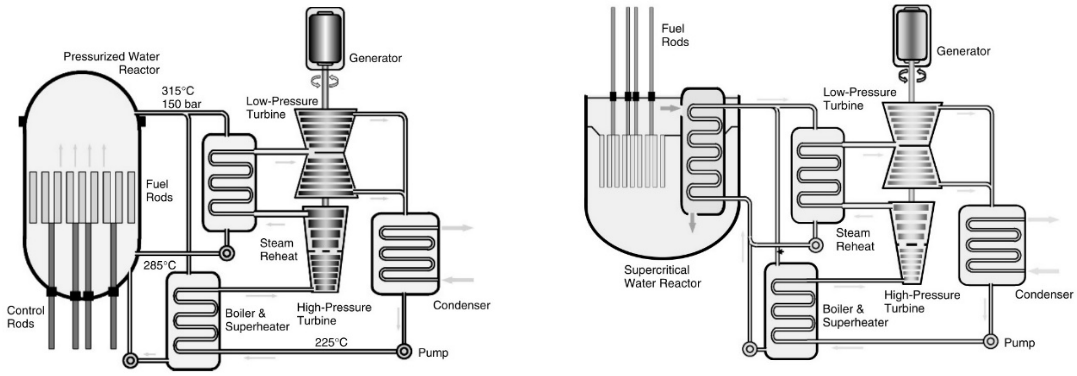
2.1. Operation principle and characteristics

The average installed capacity of a typical small nuclear reactor is roughly 5 to 40 times smaller than a regular large nuclear reactor. It has an electrical power output of 50 to 300 MW, while large nuclear reactors normally have power outputs between 1,000 and 1,700 MW. Small reactors are often described with the acronym SMR, which comes from the words Small Modular Reactor. The term small is usually connected with their power output, while the term modular is connected with their ability to be combined or extended as separate modules resulting with power plants with a desired power output. In addition, there are also the so-called micro-reactors that are even smaller, with a capacity less than 50 MW. However, they are usually used for isolated communities, remote mining activities, for small island electricity grids, and even for military outposts or camps where they replace expensive and hard-to-transport diesel generation.

The most common and technologically mature type of a nuclear reactor is the light water nuclear reactor. There are also molten salt reactors, metal cooled reactors, gas cooled reactors, thorium and uranium fuelled reactors, etc. One important property of all of them is output temperature, which can be anywhere between roughly 90°C and 900°C and enables different and new applications for nuclear energy. These small reactors have a term called *"passive safety."* Passive safety means that the reactor, if something unexpected happens, shuts down and cools itself without external help such as electric pumps. For example, the reactor might sit in a large pool of water that can cool off the residual heat after shutdown. Various designs of SMRs would become available in near future, particularly during the 2020s and 2030s, which means that most countries need to start reforming their regulations and legislation today.

The most prominent difference between large nuclear reactors and the SMRs is the fact that SMRs are manufactured off-site and then delivered to their designated location for final assembly. This results in less on-site construction, heightened nuclear security and increased containment efficiency. SMRs are seen as a preferable approach to overcome the financial barriers that can inhibit the production of a conventional nuclear reactor. Additionally, SMRs can offer a carbon free, clean energy alternative to fossil fuels, just as with conventional nuclear reactors.

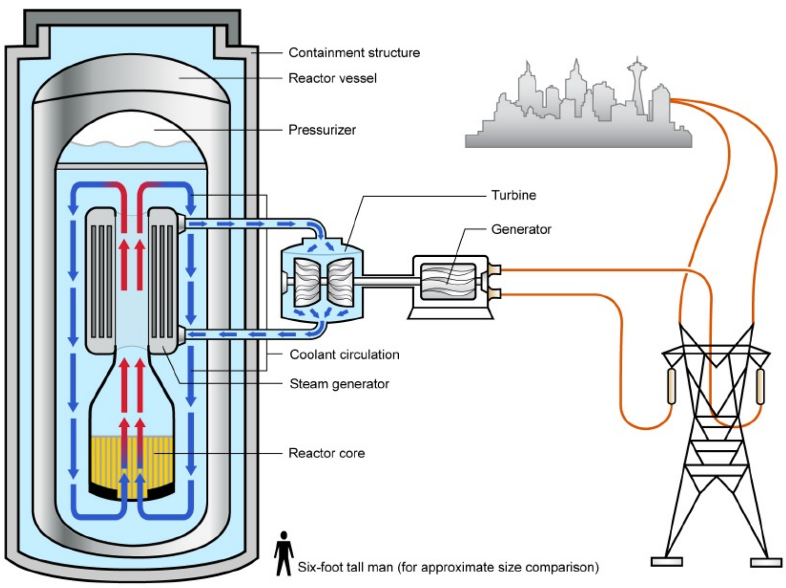
SMRs currently use, similar to large nuclear reactors, nuclear fission as the basis for producing energy. Nuclear fission is the process by which the nucleus of an atom splits into two or more smaller, lighter nuclei. The split atom releases large amounts of energy in the form of heat and radiation. This causes a chain reaction, which needs to be sustained and controlled to generate safe and reliable nuclear power. Designs include thermal-neutron reactors and fast-neutron reactors. The difference between the two is the speed in which the neutrons flow. Thermal-neutron reactors rely on a moderator to slow the travelling speed of the neutrons and primarily use uranium as the fissile material. Fast-neutron reactors do not use moderators and rely on the nuclear fuel being able to absorb the neutrons travelling at higher speeds. Typically, fast-neutron reactors use plutonium as fissile material. To date, most operating nuclear reactors use the thermal-neutron approach [5].



Thermal-neutron PWR *Sodium-cooled fast reactor*

Figure 2. *Comparison between thermal-neutron and fast-neutron nuclear reactors [5]*

Like conventional nuclear reactors, SMRs harness thermal energy to generate electrical power, as shown in Figure 3, [6].



Source. United States Government Accountability Office, Report GAO-15-652.

Figure 3. *Light-water small modular nuclear reactor (SMR) [6]*

As shown in Figure 3, the thermal energy generated within the reactor's core heats water into steam, which then powers a turbine generating electrical power. As of 2018, several SMRs have already been proposed, applied for licensing or constructed as testing facilities worldwide. For example, the Chinese high temperature gas cooled HTR-PM was expected to start operations by the end of 2019, and the pool-type district heating reactor DHR400 should also be ready in a couple of years' time, according to China's energy news. Also, many of the western reactor vendors work or they are planning to have their first SMRs finished during the coming 2020s, which means they will start construction in a couple of years. However, only the Russian Rosatom company OKBM Afrikantov based in Nizhny Novgorod, in May 2020 put into commercial operation the SMR "Akademik Lomonosov-1," one of the two small KLT-40S floating reactors on a barge that can be towed to a suitable location. This SMR is based on the previously developed OK-150 and OK-900 small nuclear reactors for powering Russian icebreaker ships. This KLT-40S has the installed electric power output of 32 MWe.

The key bottleneck today for larger inclusion of SMRs in the western countries is not the technology availability, but the lack of proper regulation and legislation for them. This can take many years to be properly done, thus these activities need to start as soon as possible. The current regulations are written for large reactors producing electricity far from population. Some of the key uses for small and advanced reactors is producing electricity and heat at a smaller scale nearer to population or other industrial activities. This shift requires new legislation and regulation, and no company will start a project unless there is regulatory certainty.

In addition to the above mentioned SMR projects in China and Russia, there are dozens of other SMR designs and companies worldwide. Intensive research and development of new reliable SMRs are in the advance development phase in various countries, such as South Korea, USA, UK, France, Japan, even in Sweden, Denmark, Argentina and Indonesia. There are currently more than 50 projects under development and 6 types of small nuclear reactors under investigation, showing that the SMRs bring new challenges with a new operational concept and reduced problems of traditional large nuclear power plants.

Figure 6. *Typical appearance of a SMR*

2.2. SMRs in combination with renewable energy and thermal storage

The electricity grid of the near future is likely to have much higher shares of renewable energy sources, specifically wind and solar power plants. This poses challenges and increases the costs of keeping the grid stable, as the production from wind and the sun, on one side is largely unpredictable, and on the other side it can go up or down very fast. Hydropower is good for providing flexibility, stability and back-up for windless days, as are natural gas turbines, but both have their own problems. Hydropower cannot be scaled up much from current levels, and has seasonal problems with available waters mainly as a result of the global climate changes, while natural gas is a fossil fuel with emissions, its supply is sometimes problematic and unsecure, such as at present time due to the Russia-Ukraine crises, and finally it has highly volatile market prices.

Many of the SMRs that are being designed aim to provide similar services as natural gas-fired and hydro power plants already do. Their advantage is that nuclear can be scaled up almost without limits and it does not produce emissions. Nuclear reactors produce hot steam that is turned into electricity in a turbine-generator units. To add flexibility to the electricity production, a high temperature thermal storage can be used to store the heat from the reactor. Later, this heat can be turned into electricity in a turbine generator as needed or as necessary [7]. This is potentially a very cost-effective way to add clean, firm and flexible production capacity to the grid, especially for grids with large quantity of renewables. Other designs, like molten salt reactors from Terrestrial Energy [8] and Moltex Energy [9], can use molten salt thermal storage and extra turbines to enable a more flexible production.

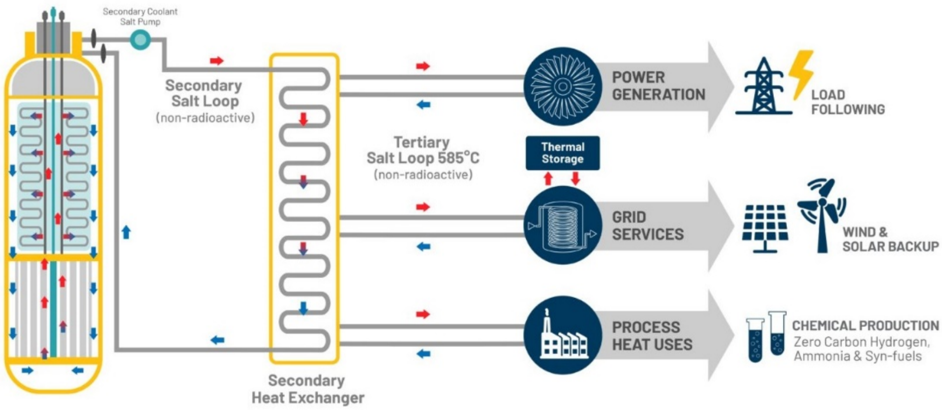


Figure 4. *The Terrestrial Energy's Integral Molten Salt Reactor® (IMSR) cross-section*

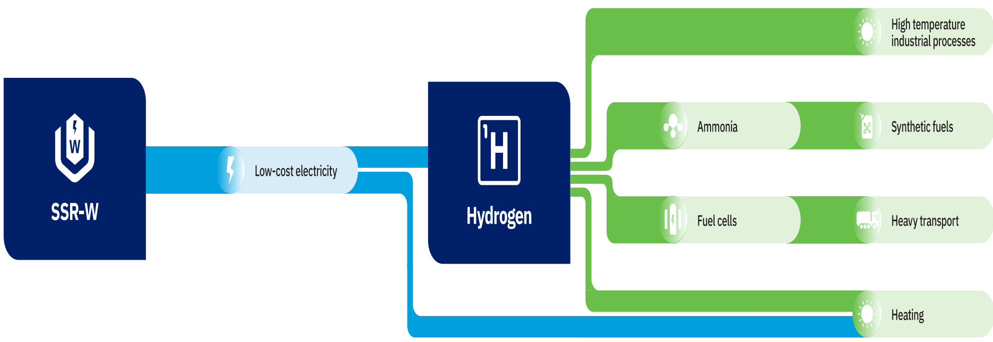


Figure 5. *Easy production of hydrogen with the Molten Energy's SSR-W reactor*

The Terrestrial Energy's IMSR (*Integral Molten Salt Reactor®*), provides a power system that is carbon-free, low-cost, high-impact, flexible and resilient, and, as shown in Figure 4, it can produce electricity, balance mechanism for renewable power energy through heat thermal storage and additionally process heat for industry, mainly for hydrogen generation. Similar advantages is provided by the Moltex Energy's SSR-W reactor (*The Stable Salt Reactor – Wasteburner*) shown in Figure 5, that in addition could burn recycled nuclear fuel and produce large quantity of heat that can be used for hydrogen production. Both reactors provide additional thermal storage combined with extra turbine-generators which could enable the reactor's power output to vary e. g. between 0% and 200%, while the reactor itself would run at full power all the time.

Large nuclear reactors have traditionally been used for electricity generation. However, many of the newly designed SMRs, beside electricity generation, can be used in parallel for other things as well [10], [11]. While electricity accounts for only 20% of our global energy use, roughly 50% of our energy is used as heat, and additionally around 25% is used in the transportation sector. Industries such as refineries, chemical plants, pulp and paper mills, manufacturing plants, metal and cement production and many others, alongside electricity use high grades of heat, and could be particularly well suited for the utilization of SMRs.

Finally, speaking about heat utilization, around 2/3 of heat is used at relatively low temperatures of around 80°C to 120°C. This includes space heating and hot water use and some industrial uses. These temperatures can also be used for water desalination and district cooling [12]. Such low temperatures can be made reliably and cost-effectively through many means, including waste heat streams with heat pumps, combined heat and power (CHP) in power plants and heat-only nuclear reactors. However, utilization of a SMR that makes low-grade heat can be very simple and straightforward. For example, such SMR could sit at the bottom of a so-called *"swimming pool"* and just heat the water that is then used for district heating, desalination or something else. As no electricity is produced, this type of SMR does not need pressure vessels, steam generators or turbines, making its design very modest with lower investment cost.

3. Economics of SMRs

These advanced SMRs should be much more affordable to build than conventional large power nuclear reactors. These types of reactors avoid the huge upfront costs associated with the long-term planning and lead times of conventional reactors [13]. SMRs enable modular build of power generation systems. This allows distribution of build costs over a longer duration. For example, an individual SMR could be built in four or five years, then once operational it will generate revenue to aid funding of additional modular units, if required. Owing to SMRs being built in larger numbers in factories, manufacturers will be able to better implement processes typically used in industry to drive down costs, such as buying high-value components in bulk, which is not possible for one-off, location-built large reactors.

Regarding energy output costs, initial cost models suggest that SMRs will not be significantly cheaper per unit of energy produced. A 2014 study led by the National Nuclear Laboratory at the University of Bristol, UK, gives a best estimate of over £80/MWh, which is comparable to the agreed strike price for some new nuclear reactors that are currently under development. However, Rolls Royce Energy Division is targeting a price of only £60/MWh for its SMR designs, which is highly affordable for such advanced technology.

We have to keep in mind that if we are to successfully limit climate change, having in mind the amount of generated energy, operational life expectance, predictability and reliability of electricity and heat generation, nuclear may be a better alternative than increased investments in various renewable sources. As fossil-fuel prices rise, the cost of nuclear power, which was once deemed too high, now becomes competitive. Even countries that withdrew from nuclear energy use after the 2011 Fukushima accident, such as South Korea and Japan, have stated their desire to recommit to the technology.

In the near term, new reactors will be built from existing designs. These large, water-cooled reactors produce between 600 megawatts electric (MWe), such as Canada's CANDU reactors [15], or 1,650 MWe at Hinkley Point C by France's EDF. They have excellent operational characteristics with very low-down time, meaning they generate electricity more than 90% of the time and have design lives of 60 years. However, they take an average of nearly 8 years to construct, and sometimes longer, e. g. Finland's Olkiluoto 3 reactor took 16 years, and some should be postponed for better times or even abandoned, such as Belene nuclear plants in Bulgaria. The large up-front costs, usually in the order of billions of dollars, and long delay before investment is returned has deterred investors who want assets that can be built more quickly and more cheaply.

SMRs aim to address these issues, and could be deployed by the end of the decade. The SMR concept puts an emphasis on factory construction, which enables advanced manufacturing methods and a reduction in on-site construction and consequent weather delays. These reactors target power levels in the range of 70 – 500 MWe. Because construction timelines are half that of large reactors, SMRs reduce unit price to levels suitable for private investment, although multiple units will be required to produce the same output as a larger plant.

The main barrier to the success of SMRs lies in attracting sufficient orders to cover the cost of development and a factory. Even if this is achieved, siting and licensing may still be obstacles. Current national regulatory systems, which differ widely, are geared towards a small number of large projects, with each often taking years to be approved. This will need to be streamlined if the rapid development of an SMR fleet is to be practical. As we saw in the previous chapter, SMRs beside electricity generation could support processes such as desalination, paper production and drying, as well as district heating and domestic hot water supply through district-wide heating schemes. There is a long history of nuclear district heating in countries such as Switzerland, Sweden and Canada, but their high infrastructure cost has deterred widespread use.

This large district heating systems based on SMRs utilization could become competitive, however, if gas prices fail to fall significantly, which is the case in recent years. Some projections for a scheme to heat Paris from large reactors estimated a cost of €42 per MWh [16]. This compares well to gas prices before the Russia – Ukraine conflict. Taking into consideration the current gas prices, these projections become highly feasible. Cost could also be reduced further through the use of SMRs, the aim of which is generation of electricity and heat be placed closer to population centers, reducing the length and cost of the heat transmission network.

New-generation high-temperature reactors are also being developed by several countries, which suit applications such as iron smelting and efficient hydrogen production via steam electrolysis and thermochemical routes with the latter one having been demonstrated at pilot scale already, with Japan's high-temperature test reactor.

Although new enthusiasm for nuclear power may be driven by the same factors of energy security and price as the oil shock of 1973, its ability to provide low-carbon electricity and process heat means it is perhaps an even more relevant choice for today's energy systems than it was back then. By doing more than just producing electricity, it can aid in deep decarbonization by displacing oil and gas, which also reduces the geopolitical power that can be wielded by those who control its supply.

4. Conclusions

Given the opportunities SMRs present, there is a need to push for SMR technologies as a viable nuclear energy option to meet both the growing global energy needs and the search for low-carbon energy options. In comparison to large-scale nuclear power reactors, SMR technology provides a simpler and inherently safer opportunity for the expansion of the nuclear energy sector. SMRs have lesser fuel requirements, smaller physical area requirements and hold the potential for a large-scale factory production, transportation, and installation globally. Given the interest and active participation from both the public and the private sectors in countries such as Argentina, Canada, China, Russia, United Kingdom, USA, and South Korea in SMRs, the future of nuclear power as a viable energy alternative is predicated upon actualizing the SMR technology potential at a global level. To achieve the Sustainable Development Goal of universal access to energy [17], SMRs and nuclear power offer more efficiency and flexibility to meet energy demands than other renewable alternatives such as wind and the sun.

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