Small Modular Reactors (SMRs): reality or fantasy?

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(CNR[1] retired researcher)

Introduction:

Global warming, which seems to have accelerated in recent years, is mainly caused by the release into the atmosphere, as a result of human activities, of so-called greenhouse gases, of which carbon dioxide, CO_2, is the main one.

Traditional power plants, which rely on fossil fuels (coal, oil, or gas), are among the causes of global warming.

Drastically reducing CO_2 emissions into the atmosphere has become an urgent task.

In this context, modern technologies for the direct production of electricity from renewable sources, such as wind, geothermal or photovoltaic plants, represent an indispensable and viable alternative to the use of polluting fossil fuels.

In recent decades, however, a new push has also grown towards the greater use of nuclear energy, considered as a carbon-free technology, including through the proposal of new generation, modular nuclear reactors with a power not exceeding approximately 300 MW electric, called 'Small Modular Reactors' (for brevity, SMRs).

This perspective was also recently revived by the European taxonomy, which entered into force in 2023, where innovative nuclear plants have been included in the list of those that the EU will be able to fund directly for environmental

[1] *CNR, *Consiglio Nazionale delle Ricerche*, National Research Council

sustainability and to achieve the ambitious climate neutrality objective (i.e., 0 net CO_2 balance in the atmosphere) by 2050.

Small Modular Reactors: the EU definition

The EU has dedicated some Web pages that define what can be considered SMRs.

It reads:

"SMRs are defined as small nuclear reactors with a maximum output of 300 Megawatt electric (MWe) and can produce 7.2 million kWh per day. By comparison, large-sized nuclear power plants have an output of over 1,000 MWe and can produce 24 million kWh per day. SMRs can vary in size from around 20 megawatts electric (MWe) up to 300 MWe and can use a range of possible coolants including light water, liquid metal or molten salt, depending on the technology."

It should be noted that the definition refers to the electric MW: taking into account the average performance of a nuclear installation, around 30-40%, the thermal power of the plant will be higher; 300 MWe will correspond to about 900-1000 MW thermal (MWth).

The official internet pages add additional safety-related information:

"SMRs are harnessing the operating experience from traditional large reactors, as well as the use of small-scale reactors in nuclear submarines and other nuclear-powered vessels, such as icebreakers.
SMRs have passive (inherent) safety systems, with a simpler design, a reactor core with lower core power and larger fractions of coolant. These altogether, increase significantly the time allowed for operators to react in case of incidents or accidents.
SMRs safety principles mostly rely on simple phenomena like natural circulation for the cooling of the reactor core, even during incident or accident situations requiring very limited, or even no operators' actions to bring the reactor to a safe state in case of need.

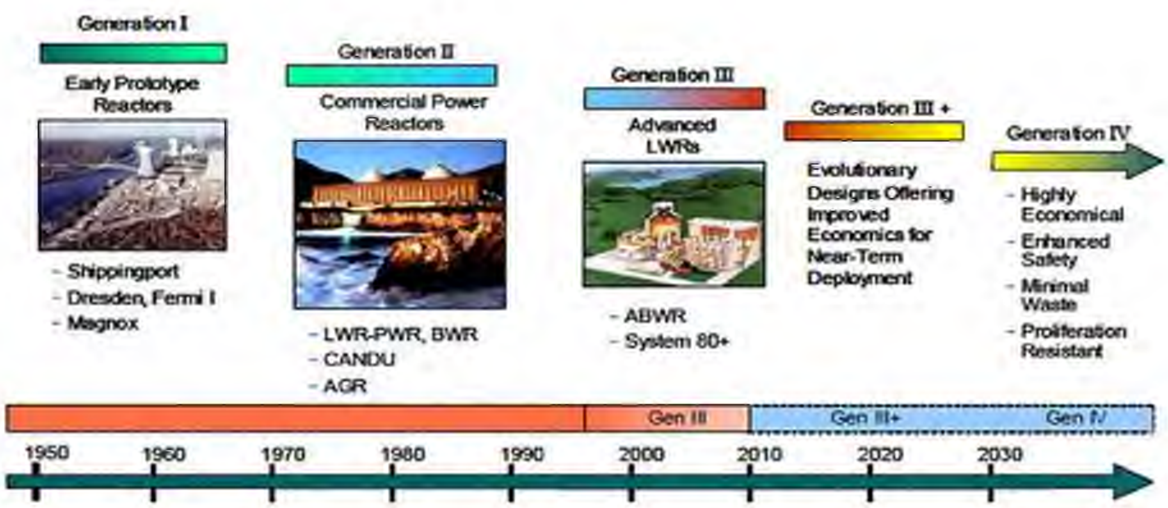
These passive safety systems also allow elimination of a range of components, valves, safety grade pumps, pipes and cables limiting de facto the risk of their failure.“

The EU internet pages also mention the reasons for financing these systems: ranging from the capacity to stabilise the electricity grid, to their modularity and flexibility and to the reduced use of water for cooling, to the fact that they can replace fossil-based production systems and the ability to create skilled jobs, and finally to their use for the co-generation of electricity and thermal energy (given their planned location close to residential areas or industrial sites).

In summary: very positive and reassuring information. There is no mention on these official pages of radioactive waste, environmental impact or other critical aspects, such as nuclear proliferation, which I would like to discuss in this note.

Nuclear reactors: past and future

The figure below shows the evolution in time of successive generations of reactors.



First-generation (**Gen I**) reactors were operating in the 60s/70s and no longer exist.

The second generation (**Gen II**) reactors are PWRs (Pressure Water Reactors) and BWRs (Boiling Water Reactors), representing about 2/3 of the reactors still in operation.

As for the third generation (**Gen III**), there are 2 in operation in Europe (1 in Finland and 1 in France), which required very long construction times and very high costs (17 years and 13 billion euros for Flamanville in France). They are also referred to as EPRs (European Pressure Reactors).

In this industry sector, China is building many dozens of PWRs called *Hualong one*, which are considered to be Gen III.

The fourth generation reactors (**Gen IV**) should solve all or almost all the problems of nuclear power related to costs, safety, waste, environmental impact, etc.

Currently, they only exist as projects.

SMRs can be Gen. II or III, but most projects aim to be Gen. IV.

In addition, to trigger the fission chain reaction, all reactors currently in operation around the world use thermal (or slow) neutrons, i.e., neutrons slowed down by a medium called 'moderator', whose rods extractable from the core can accelerate or slow down nuclear processes, constituting the reactor's main control system.

In the new SMR concepts, however, there are also designs that want to use 'fast' (not slowed down) neutrons. These designs are also called 'breeders' because they can, in principle, generate more fissile material than they consume, thus creating an energy cycle that may not require periodic introduction of new fissile material (or the refuelling would only be rarely needed) and therefore generate, in theory at least, a low amount of radioactive waste.

SMRs: current situation

There are many different SMR designs around the world that use different patterns of operation, different fuels, and different types of cooling.

Here we will try to give a brief description of the current situation.

The picture shows the geographical location of the various projects and their degree of development (colour-coded). It is clear that very few plants are in operation.

The International Atomic Energy Agency (IAEA) has created a website where a lot of information about SMRs is collected:
https://nucleus.iaea.org/sites/smr/SitePages/SMR-Databases.aspx

From the Aries database (https://aris.iaea.org/TechnicalData/) it appears that there are approx. 120 different projects in the world. Almost all projects are under development.

The main new projects can be categorised in:

- Gas-cooled SMRs
- SMRs with liquid metal cooling and fast neutrons (breeder)
- SMRs with molten salt fuel

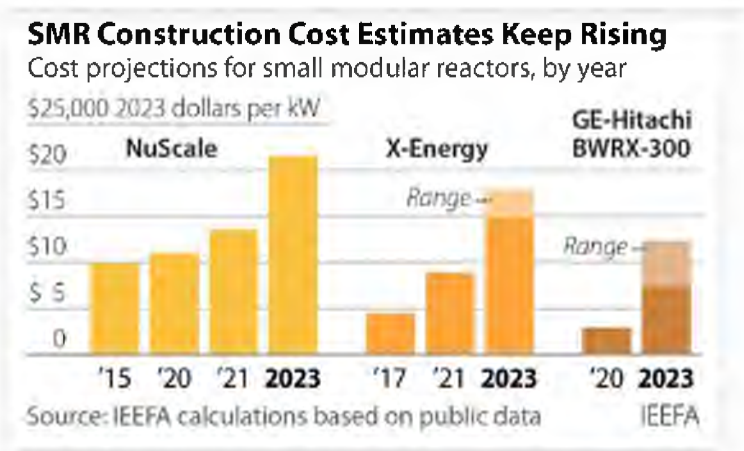
The only SMRs currently operating are in Russia and China.
While a couple of Gen II reactors are operating in Russia, a Gen III reactor (called *Linglong One)* and a demonstration plant have just been in operation in China (along with a couple of other Gen II reactors). The demonstration plant, the 250 MWe Shidao-Bay HTR-PM, is considered a significant step towards a Gen IV reactor.
The HTR-PM project entered commercial operation in December 2023. This reactor should be intrinsically safe as shutdown tests in the absence of auxiliary systems appear to have been successfully performed in 2024.
The estimated cost of the Shidao-Bay plant was about USD 500/600 million and construction took approximately 11 years. The HTR-PM (High-Temperature Reactor-Pebble-bed Modules) plant uses 8.5% enriched uranium dioxide particles encased in graphite spheres (about twice as much as a conventional reactor) and is gas-cooled.
The Shidao-Bay site also houses two 1500MWe conventional reactors (PWRs) each.
It should be noted that high-grade enriched uranium spheres have several production problems related to neutron fluxes and plant safety. In addition, there are problems related to possible misuse through the removal of the finished product (given the small size of the spheres, approximately 300,000 are needed for the reactor).
You should also note that the project foresees the construction of other similar units, but this has not yet begun. Furthermore, there is no news of the true reliability of this plant, while it is known that its operating power has been halved for now.
Almost all other SMR projects outside of China are either in the early stages of the project or in the 'licensing' stage, and still face too high estimated cost issues.
One example among many is the US project, *NuScale*, which had already reached the 'licensing' stage, that is, a project authorised by the supervisory authorities,

and which was stopped due to cost overruns. Now the American company is trying to sell the project to third countries.
Note that the *NuScale* project started in Oregon in 2014 and has since obtained about $600 billion in government funding!
Recently, in May 2025, *NuScale* obtained a new licence from the US authorities to build an SMR of approx. 77 MW which should, in theory, reduce the costs.

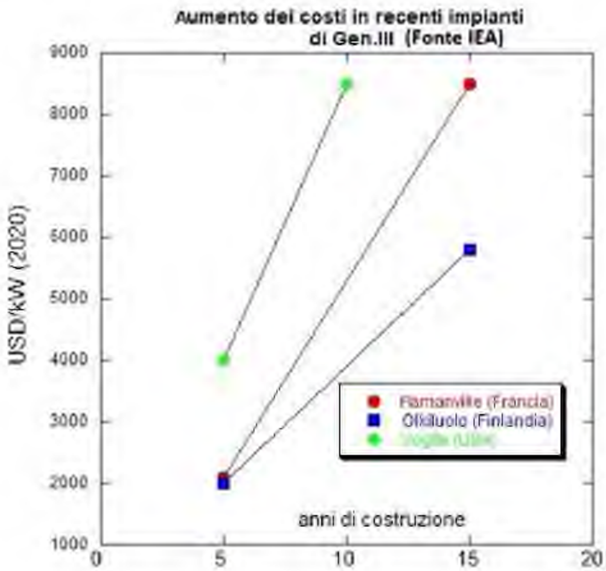
SMRs: high costs

From the chart below you can see that SMR project costs are, regardless of the project, almost tripled from their initial estimates.

Of course, the small size of these reactors does not contribute to the economies of scale.



As is well known, the cost of nuclear power generated kW is now very unattractive, even for conventional plants, compared to renewable energy sources.



Aumento dei costi in recenti impianti di Gen.III (Fonte IEA) = Increase in costs in recent Gen. III nuclear installations (Source IEA)

Anni di costruzione = Years required for construction

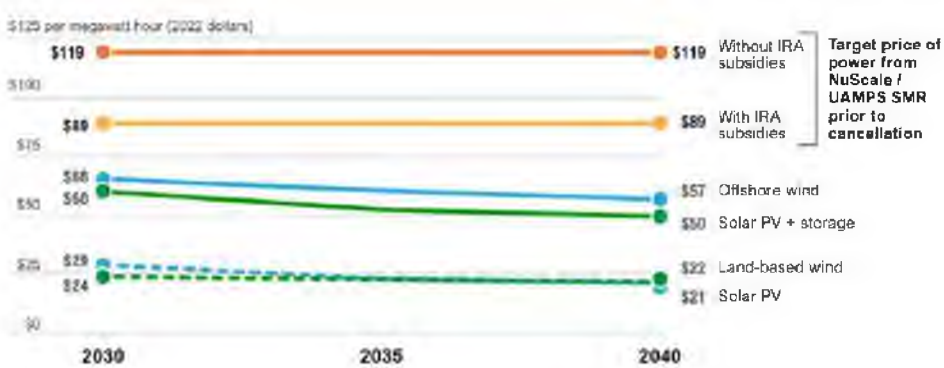
Francia = France

Finlandia = Finland

The figure above shows the increase in costs in recent nuclear installations.

Substantial state funding is therefore required to cover the extra costs and uncertainties of the markets. It is also for this reason that nuclear power has been included in the European taxonomy, as we have already mentioned.

Finally, the expected cost of SMRs of the *NuScale* type or similar is still much higher than for systems using renewable energy plus energy storage, as can be seen from the graph below (cost per MWh produced).



Source: IEEFA analysis based on data from NuScale, UAMPS and NREL.

SMRs : waste, environmental impact and nuclear proliferation

Let us now turn to the very sensitive issue, although hardly ever mentioned in relation to SMRs, of radioactive waste. Of course, because SMRs include very diverse reactor designs and there are no prototypes for them, a detailed discussion is virtually impossible.

In a recent work[2], however, an analysis of 3 types of SMRs, sodium-cooled Toshiba 4S reactors, NuScale iPWRs and Terrestrial Energy Integral Molten Salt Reactors, shows that these technologies can produce up to 30 times the waste produced in large reactors per MWh. Furthermore, due to the small size, lost neutron fluxes can activate the materials surrounding the reactor, with up to 10 times the amount of material activated compared to large plants, where neutrons are better confined in the core. Indeed, all neutrons that are not used for the chain reaction occurring in the reactor core are lost and contribute to the radioactive activation of the surrounding material, generating a large amount of waste that will have to be disposed of and stored during the dismantling of the reactor.

The latter problem may become unsolvable in SMR breeder designs, where fast neutrons are intended to be used, and where losses of high-energy neutrons from the core will become very significant. The difficulties and costs of dismantling these SMRs also appear to be high. In fact, disposal of radioactive sodium or molten salts can require complex processes, increasing the risk of environmental and operator contamination.

IAEA warns on its web pages that some SMRs, particularly those that do not use water as coolant, can generate new forms of radioactive waste, so countries that want to use these facilities must plan how to treat this waste.

It should also be added that nuclear reactors consume for their cooling (primary and/or secondary) and for the production of steam an important natural resource: water. Among other things, as has been proven by recent cases in France, in the case of particularly hot summers (which are becoming increasingly frequent), the water used cannot be fed back into the waterways, in many cases

[2] 'Nuclear waste from small modular reactors', Krall et. al. Environmental Sciences, 119 (23)

resulting in the temporary shutdown of the plants and/or their decommissioning, causing, in this case, problems for the electricity grid.

Furthermore, very often when calculating CO_2 emissions from nuclear energy, waste disposal and management are forgotten. The near-zero emissions figures are therefore not realistic. More reliable estimates, including emissions from power plant construction, uranium mining, fuel bar enrichment and manufacturing, and waste transport and storage, bring emissions from this source to approximately 80-100 g CO_2 per kWh produced. Thus, about a quarter of fossil-fuel emissions, but definitely not zero, as is often said.

Finally, there are the problems associated with the possible misuse and proliferation of small and widespread nuclear plants in various countries. Among other things, it must be said that many developing countries in Africa and other continents have declared their interest in these technologies. Companies in this sector expect the market to be global, also to cover the design costs that lasted many years.

In this global market situation, and taking into account the fact that many of the countries concerned have unstable political systems, plants are exposed to terrorism and environmental risks due to climate change (the latter observation is unfortunately true for everyone!). Understandably, an analysis of environmental and proliferation risks is very difficult, if not almost impossible. In fact, in a work[3] in which many nuclear experts are asked for an opinion on the risk of proliferation of SMR reactors, the opinions are very different.

The study refers to a hypothesis of 4700 SMR plants producing an average of 100 MWe each.

Ultimately, I think that it is impossible to argue that the SMRs do not pose serious problems of radioactive waste and environmental safety, or that they do not pose very serious problems of safety in general, through the possible misappropriation of radioactive material and its misuse and their possible placement in countries with unstable political structures and undemocratic governments.

SMRs: the contribution to the overall energy balance

It is quite clear from what we have seen so far that the use of nuclear power, even of a new generation, will only make a residual contribution to the energy needs of the planet in the near future.

This is mainly due to the long construction time, the number of reactors that would need to be built, and the high costs involved in all stages from design, plant safety and waste disposal.

Finally, we must remember that the natural resources of uranium are limited, and their duration depends heavily on the number of plants that will use it in the future.

[3] '*An Expert Elicitation of the Proliferation Resistance of Using Small Modular Reactors (SMR) for the Expansion of Civilian Nuclear Systems*', J. Siegel et. al. Risk Analysis, John Wiley & Sons, vol. 38(2), 2018

Furthermore, the development of nuclear energy requires, as we have seen, a great deal of public money, which cannot therefore be used for other purposes, for example, for the development of renewable energies.

A recent and in-depth study[4] by the Bank of Italy, "The fleeting atom: analysis of a possible return to nuclear power in Italy" available on www.bancaditalia.it, reaches similar conclusions. It contains up-to-date data and extensive technical and economic analyses.

As regards the so-called stabilisation of the grid, i.e. that nuclear power is a continuous source of production, when compared to renewable sources, and could therefore provide the necessary stability to the electricity grid, I believe that the development of storage systems and the ever-increasing integration and interconnection of power grids can also serve this purpose at much lower costs, as can be seen from the graph on the costs of the various sources shown above. It should also be noted that with the development of smart grids, large (nuclear and non-nuclear) plants seem to be less and less adaptable to a philosophy of electric power transmission based mainly on the flexibility of fluxes: the grid provides energy to end-users but can also receive it from end-users and redistribute it quickly, with reaction times not appropriate for large plants.

Keep in mind that, while electricity supplied from renewable sources continues to grow at high rates around the world, and is expected to cover 50% of global production by 2030, whereas worldwide electricity from nuclear sources has fallen from 16% to 9% in the last 20 years.

Big-Tech interest in SMRs

In this section I want to highlight a political rather than scientific aspect, which can, however, explain the worldwide emphasis placed on the development of SMRs.

Big-Tech companies are involved in many SMR projects.

[4] L. Lavecchia and A. Pasquini, '*L'atomo fuggente: analisi di un possibile ritorno al nucleare in Italia,* Banca d'Italia, June 2025, No. 947

Virtually all of them from Microsoft, Google, Amazon, etc. have their own plans for new compact nuclear reactors.

It is clear that for these companies, these investments are a way of differentiating their core business in the hope of future high profits, often benefiting, as we have seen, from large subsidies of public money; on the other hand, recent turbulent and rapid developments in artificial intelligence (AI) are driving these companies to develop grid-autonomous energy systems that can generate the vast amount of electricity required by AI.

These major technical and financial giants are little interested in the critical issues we have so far analysed: environmental impact, widespread risk, waste management, and nuclear proliferation. Their goal is to maximise profit, possibly offloading all risks to the public.

In an interesting essay[5] recently published "Bright Science, Dark Science", chemist Gianfranco Pacchioni addresses the issue of the progressive transfer of research and knowledge from the usual areas of laboratories and public universities to Big-Tech companies. This relocation is leading to the suppression of research findings and an ever greater increase in earnings for these companies, which have become genuine monopolies of knowledge in certain sectors. AI is a striking example. Studies and patents in this area are now in the hands of a few companies which are using the information provided free of charge by people, laboratories, and universities to increase their influence, monopoly, and ultimately their profits. These technological oligarchies now have a political/financial weight equal to that of the states, jeopardising the very concept of democracy.

The new SMR projects carried out by Big-Tech companies are therefore perfectly part of this logic of growth in profit, of increasing their influence in the various strategic sectors of society, and also of relying on substantial public funding.

If these projects are carried out in the future and if they are likely to cause serious environmental damage, it is almost obvious that the costs will be borne entirely by the states and their citizens.

[5] Gianfranco Pacchioni, '*Scienza chiara, scienza oscura*', Il Mulino publishing house, 2025

Conclusions

Ultimately, the following conclusions can be drawn from this brief analysis:

- The cost and time of building SMR type reactors are too high.
  They do not appear to be at all competitive with the costs of production from renewable sources. Costs that are expected to fall in the coming years.

- SMR designs are not standardised and create problems in determining, from the start, the type of waste, its quantity, and its environmental hazards. There are no working prototypes (with the exclusion of the ones in Russia and China). The cost analysis is also very difficult in the absence of empirical data on these new plants, of which there is no experience in the field.

- Nuclear energy's contribution to the global energy balance in the coming decades will be marginal (currently about 9% of global electricity production), even in relation to limited natural uranium resources, while systems using renewable energy are booming. Energy storage and the rationalisation and interconnection of grids can address the variability of renewable sources. Furthermore, due to the long construction times for nuclear power plants, including the new generation ones, it can almost certainly be ruled out that they could play a major role in achieving the climate neutrality envisaged by 2050.

- Relatively small nuclear plants spread across the globe still generate a distributed risk which will be difficult to control both in terms of safeguarding the territory and in terms of nuclear proliferation and misuse of radioactive material, especially when the plants are located in countries with a high risk of terrorism and/or climate crisis.

- It must be reiterated once again that the problem of long-term nuclear waste, even from traditional plants, has not been solved at all and it is still one of the fundamental reasons for limiting the further spread of this energy source on the planet. In a very large number of cases, this hazardous waste is currently stored in unsuitable sites, with very serious environmental risks in the event of a spill of radioactive material.

- Finally, it should be noted that the development of nuclear power for civil uses has in itself the germ of nuclear proliferation and its possible use for war purposes. All countries that possess nuclear weapons initially developed nuclear power for civilian use. It is practically impossible to separate one purpose from the other without a clear political will. In an increasingly conflicting world, hoping for a policy of *détente* with solely a peaceful use of nuclear power, really seems to be a pious illusion.

Taking all these complex aspects into account, it can be concluded that it is not rational and not even economically justified for our country to return to nuclear power, even if we are planning to use 'innovative' and small-scale nuclear power plants.

As the Bank of Italy's report also admits, this would only be possible through substantial public funding and would not make Italy more energy independent in any way, given that without plants for the treatment of the raw material and for the construction of nuclear fuel, we would be dependent on other countries, including Russia, which currently has a dominant position on the European continent in these sectors.

The next generation of nuclear power and SMRs seem, therefore, more than a fantastic solution, a beautiful fantasy, which could easily turn into a bad nightmare!

Finally, I would like to make a brief comment on electric power generation by nuclear fusion, an area on which I can consider myself an expert, since I have worked on it for almost 40 years.

The government's hypothesis that by 2050 there may already be a share of energy produced by nuclear fusion is absolutely to be ruled out.

Indeed, the most advanced nuclear fusion research and engineering project yet, which is being built in France and in which all the world's major industrialised countries collaborate, the so-called ITER (International Thermonuclear Experimental Reactor) experiment, will see the first plasma, for demonstration purposes only, in 2035, after countless and perhaps inevitable delays. Probably only after 5/10 years will it be possible to operate it in relevant regimes, in which fusion reactions become quantitatively significant.

But this machine will never be able to generate useful energy, as the energy produced will only be a small fraction of that absorbed by the power grid.

A further step will be needed with the construction of a real reactor capable of producing energy and feeding it into the grid. The characteristics of this machine are being studied, and in any case, many key responses will have to come from the ITER results.

As with SMRs, more compact alternative projects to ITER are under consideration in the field of fusion, but all these projects are far from being fully implemented.

It is therefore clear that the date of 2050 does not make much sense when it comes to energy supplied to the grid from a fusion reactor.

In conclusion, I hope that this brief essay will be useful in improving and deepening the debate on the next generation of nuclear power, apart from a certain euphoria among those involved and the superficiality with which this issue is generally dealt with in the newspapers and more generally in the media.

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[6] *INFN, *Istituto Nazionale di Fisica Nucleare,* National Institute for Nuclear Physics

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Small nuclear reactors (SMRs), are advertised, with increasing emphasis, as clean, safe and essential for supporting the processes of renewal in energy supply and decarbonisation. These processes are urgently needed in order to control/mitigate climate change.

In this context, this publication aims to dispel the myth of cleanliness, safety and indispensability of small nuclear reactors. Using available data, together with industry articles published in reputable scientific journals and through accurate online research, it is shown that, with high probability, none of the above benefits can realistically be achieved. Furthermore, the proliferation of small nuclear installations will only increase the production of radioactive waste and the global nuclear risk.

Finally, in addition to the negative implications for safety, economic analyses and cost projections for small nuclear power plants show, as is highlighted in this work, a lack of competitiveness with respect to renewable sources, whose production and storage costs are falling rapidly.

Roberto Paccagnella graduated in physics in 1982 from the University of Padua with top marks and honours. Subsequently, in 1987, he obtained a PhD in Energetics from the same university. In 1987, he also became a researcher with a permanent contract at the National Research Council (CNR). He worked for about 40 years as a researcher developing models for the study of magnetically confined plasmas. In this field, he collaborated on studies for the large scale nuclear fusion experiment, ITER, under construction in France.