East European Journal of Physics. 2. 17-26 (2025)
DOI:10.26565/2312-4334-2025-2-02 ISSN 2312-4334

A PERSPECTIVE ON SMALL MODULAR REACTORS: A CASE STUDY FOR GREECE

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Received February 2, 2025; revised March 31, 2025; accepted April 3, 2025

Global efforts towards decarbonization are intensifying, but the transition to a green economy comes at a high cost, which some estimate to amount to approximately $3.5 trillion dollars annual investment, most of which is upfront. This puts a strain on developing economies that possess fossil natural resources, because in giving them up they become increasingly dependent on imported energy, which comes at a high cost, in addition to costs incurred by their efforts to shift to renewable energy sources. Nuclear technology produces dispatchable and uninterrupted hydrogen, heat and electricity that can cover the requirements for base load, and interest in its adoption is rising. Small modular reactors (SMR) offer a number of advantages, particularly for countries with limited nuclear expertise. Here we briefly assess the present state of SMR systems and consider their advantages and disadvantages with focus on their potential adoption in Greece. The review discusses the history, present state and the possible future of including SMRs in the emerging Greek energy mix.
Keywords: *Small Modular Reactor; Nuclear Energy; Thorium*
PACS: 28.41.Bm, 28.50.Dr, 29.25.Dz,

1. INTRODUCTION

Following the devastating consequences of its first use in Hiroshima and Nagasaki, and its associated potential for military uses, the first Atomic Era, in which nuclear power was to be deployed for civil purposes, such as the generation of cheap and ample energy, was marked by the 1946 Atomic Energy Act and reinforced in the context of the Atoms for Peace program in 1954. Since 1951, when the Experimental Breeder Reactor 1 (EBR-1) was used to generate electricity, and until August 2023, the International Atomic Energy Agency (IAEA) reports 410 nuclear power reactors in operation in 31 countries and 57 under construction [1]. We are now witnessing the beginnings of a second atomic era, hallmarked by small modular reactors (SMRs), where nuclear power is more closely associated with critical and emerging technologies and the fourth industrial revolution, and, moreover, the energy demanding fifth industrial revolution [2].

According to the World Nuclear Association [3] about 30 countries, ranging from developing nations to sophisticated economies, are considering, planning, or starting nuclear power programs. It is expected that industrialization and urbanization will grow substantially, especially in developing countries, forcing them to compete in order to gain access to cheap, abundant and 'green' energy afforded by nuclear technology, while having limited or no nuclear expertise of their own. The capacity of the grid, the population of the skilled workforce to operate such technology, and the standard of infrastructure to support the nuclear supply chain are all contributing factors that will determine which of the developing countries that are interested in nuclear power are more likely to receive design licensing and expertise from nuclear developed nations, in order to realize their aspirations. Given the nonproliferation and safety concerns that nuclear technology raises, an additional factor is the political and social stability of a country and its adherence with international rules and policy.

Greece is classified as a High-Income Country (HIC), the second largest in the Balkans and 53rd in the world, based on gross national income, according to World Bank 2022 data. It has Uranium and Thorium deposits, and construction and manufacturing industries that, with appropriate adjustment, could evolve into nuclear reactor component manufacturing. Also, it has a well-established education system that produces professionals in various fields relevant to nuclear energy, including engineering (across the full spectrum of electrical, mechanical, civil, chemical, but as yet not nuclear engineering per se), computer science, materials, environmental science and so on. The Greek grid has been undergoing substantial expansion in order to accommodate increasing numbers of renewable energy sources, and using this experience, it is well positioned to undergo further expansion, in order to be able to accommodate nuclear energy sources. Moreover, though in a dire state at the time, Greece strived to participate in the first atomic era, and at some point, developed expertise and possessed human capital that could be used to drive its participation to the second atomic era marked by SMRs.

We argue that the adoption of nuclear energy through SMRs in Greece could transform its industrial (and hence economic) development, open opportunities for its participation in the global nuclear supply chain, and enable its contribution to the global decarbonization effort. As Greece is representative of a class of similar countries (in terms of

Cite as: A. Chroneos, A. Daskalopulu, I. Goulatis, R.V. Vovk, L.H. Tsoukalas, East Eur. J. Phys. 2, 17 (2025), https://doi.org/10.26565/2312-4334-2025-2-02

economic growth, grid condition, and supply chain capabilities) we hope that this case study will contribute to stimulate further consideration of the adoption of nuclear energy by them, too, and perhaps inspire fruitful collaborations towards this goal.

The rest of the paper is organized as follows: Section 2 expands on Small Modular Reactors and their position in the evolution of nuclear technology. Section 3 focuses on the advantages and disadvantages of SMRs. Section 4 presents the historical context within which Greece developed scientific infrastructure and human capital for nuclear technology. Section 5 addresses the main concerns that have been raised for nuclear energy in Greece and outlines some of the positive prospects. Finally in Section 6 we present our conclusions in summary.

2. TECHNICAL ASPECTS AND THE EVOLUTION OF SMALL MODULAR REACTORS

The understanding of the physical properties of materials is essential to improve energy related materials for superconductor, fusion, fission, battery and fuel cell applications [4-18]. In most systems atomistic modelling techniques can offer complementary perspectives to experimental work, thus accelerating progress [19-23]. In the present environment where there is the requirement for a sustainable transition to net-zero CO_2 emissions by 2050 there is renewed support to new technologies including nuclear fusion and fission. Nuclear fusion considered as the future energy source is theoretically an infinite source of power with practically no CO_2 emissions, it is considered safe to operate, and a resilient energy system. There are still significant technical issues that need to be tamed for nuclear fusion technology to be in the energy mix by 2050. At the heart of the technology is magnetic confinement, which employs magnetic and electric fields to heat and confine the hydrogen plasma. High temperature superconductor materials including cuprate superconductors are essential in fusion technology as they are able to accommodate very high current densities in high magnetic fields. This improved power density in turn is a prerequisite to optimize the limited space in a tokamak [12].

DEMO is the fusion reactor that is anticipated to produce energy at a reasonable rate and the optimistic forecasts is that there will be required at least 25-30 years to reach this goal. The present state is a transition to renewables like solar and wind with fossil fuels being gradually excluded from the energy mix. This leaves a difficult task for the stabilization of the power grid and the required production of the base load. With batteries having a number of disadvantages (cost, environmental impact for the extraction of lithium etc.) and limited water resources and infrastructure (dams) to pump water in a higher potential energy state the only viable and low CO_2 emissions solution to produce the base load is nuclear power.

Uranium dioxide is the most common nuclear fuel. Xenon and helium in uranium dioxide have been studied for decades as they can have an impact on the thermal conductivity and physical properties of the fuel and spent fuel. In uranium-based nuclear fuels radioactive decay (i.e. alpha-decay) will lead to the production of helium. In prolonged time periods helium is accumulated and the consequence of its presence in nuclear fuel has to be assessed. In particular, at the end of use and in the disposal (or storage) stage of uranium dioxide-based fuels they will probably contain helium that was formed during the radioactive decay of actinides produced in the irradiation process.

The size of nuclear power plants and the associated costs for their construction, maintenance and operation, led to the development of SMRs, which are smaller in size, easier to site and license and can be constructed in a modular fashion in one location and then shipped for installation and operation in another location. Although they can operate at various power scales ranging from 50 MWe to several hundred MWe, typical SMR capacity is at 300 MWe per reactor, and their modularity allows for streamlined design and adaptability, as components can be added incrementally to meet changing energy demands. So far three SMRs are operational in Russia, China and India, three more are under construction, 65 are in the design stage and 39 are in the conceptual design stage [24]. As SMRs are considered promising for effective, widespread, and safer use of nuclear power for energy generation, with associated benefits for decarbonization and economic development in poorer parts of the world, the IAEA has launched a special purpose portal to promote technical cooperation, standardization and coordination of research projects [25]. Many regard SMRs as the hallmark of a new atomic era, for example as part of the plan to reactivate France's nuclear program, as announced by President Macron in February 2022, who plans €1 billion of investment to be allocated to the development of innovative small-scale reactors.

Nuclear reactors, irrespective of size, are generally categorized in generations, depending on their design as seen in Figure 1 [26].

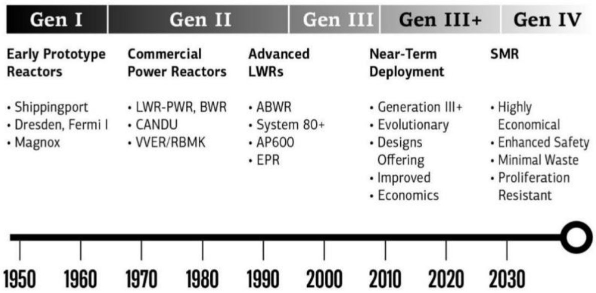

Figure 1. Evolution of nuclear reactors from the early prototype reactors to SMR [26]

The majority of current nuclear reactors in operation are generation II (or Gen II) reactors. This is a design characterization and refers to commercial reactors built until the end of the 1990s, which include pressurized water reactors (PWR), boiling water reactors (BWR), advanced gas-cooled reactors (AGR), water-water energetic reactors (VVER), and so on. The Chornobyl and Fukushima reactors belong to this design classification, although Chornobyl was an idiosyncratic dual-purpose reactor, called RBMK, which was intended for both military and civilian purposes, and does not fully merit Gen II characterization.

Gen II reactors were succeeded by Generation III (or Gen III) reactors cooled and moderated by water, also called light water reactors (LWR), followed standardized designs that afford improvements, such as better fuel technology, higher thermal efficiency, and passive nuclear safety. The improvements are said to render Gen III reactors “evolutionary designs” with a longer operational life of 60 years, possibly extendible to 100 years, as opposed to Gen II reactors that were intended for 40 years of operation, possibly extendible to 60 years. The first Gen III reactors have been operating in Japan since 1996. Gen III reactors have solved the safety problem, especially addressing lessons learned from the Chornobyl and Fukushima accidents and consolidating the “defense in depth” safety architecture of reactor protection systems.

The Gen IV International Forum for the development of Gen IV reactors, which are hailed as “revolutionary designs”, was established in 2000, but there is still no concrete deployment of such a reactor. Six designs have been selected, namely the gas-cooled fast reactor (GFR), the lead-cooled fast reactor (LFR), the molten salt reactor (MSR), the sodium-cooled fast reactor (SFR), the supercritical-water-cooled reactor (SCWR) and the very high-temperature reactor (VHTR) [27], of which the SFR is the most developed. Gen IV reactors are intended to solve the problem of economics, that is, in addition to the safety achievements of Gen III, they focus on reducing the levelized costs of Gen IV reactors to render them competitive with other power generation approaches, especially natural gas units. Additionally, some Gen IV designs aim at high temperatures to facilitate the efficient production of hydrogen.

The requirement to reduce greenhouse gas emissions (Net Zero by 2050) has led to the use of renewable energy sources (mainly solar and wind power) in synergy with nuclear units. Here nuclear can be deployed for baseload and grid security purposes because it is fully dispatchable and in addition, nuclear reactors provide emissions-free power for several years, generating not only electricity, but also, water, heat and hydrogen while ensuring grid stability and resilience, thus contributing positively to both decarbonization and energy security goals.

In the past few years there is growing research and industrial interest in SMRs. This is driven by the innovative nature of these reactors, their potential to be used in countries without civil nuclear power and their expected significant role in the decarbonization of energy production providing countries an efficient route towards net zero. Because of their smaller cost, in comparison to large nuclear power plants, and their versatility for integration they can become an essential component in the energy mix providing grid stability, security, grid resilience and energy diversification.

3. ADVANTAGES AND DISADVANTAGES OF SMR

The emergence of renewed investment in nuclear power as an essential pathway to a “carbon free future”, led to a growing interest in small and medium size modular reactors [28]. This interest in compact power units, as an alternative to conventional plants, simpler in design, easier to site and license, and faster to build as well as to connect to the operating electricity grid, aims at achieving for nth-of-a-type reactors levelized costs competitive with gas. The term ‘levelized costs’ refers to the average cost of the energy produced over the lifetime of a generating unit. Nuclear units are very capital intensive, requiring that nearly 80% of the total cost incurred (from inception to decommissioning) to be spent upfront, that is before any power is generated. SMRs are expected to have significantly smaller licensing, siting and construction costs (all incurred before energy is produced) and therefore lower investment risks. Importantly, SMRs development involves innovative smart systems where, with the help of digitization and artificial intelligence (AI), the financial burdens for operations and maintenance as well as security of nuclear materials are reduced [29].

In mid-level countries with respect to industrial and demographical considerations (such as Greece) that are committed to the energy (or green) transition, decisions about the future energy mix (i.e., coal, oil, natural gas / liquefied natural gas (LNG), renewables, hydro, nuclear, etc.) require multicriteria analysis. SMRs can be considered as an efficient, cheaper and feasible alternative source of electricity (and fuel) generation technology (note: historically Greece has strived to participate in the atomic age initiated by the Atoms for Peace Initiative in 1950s, refer to Section 4 below).

With simplified licensing, siting, construction, and digitization, SMRs are expected to have significantly lower total investment costs compared to the conventional large nuclear stations and require reduced investment in the transmission grid if built to replace retiring fossil fuel units. In the US, through the Inflation Reduction Act (IRA) of 2023 there are strong incentives to convert retiring carbon producing coal plants with emissions-free SMRs to take advantage of existing transmission lines.

SMRs are particularly attractive for new generation nuclear power technology for countries with land and natural risks, which limit the potential for renewable energy (for example Japan). SMRs can have similar operating conditions and fuel arrangements with most types of large nuclear power plants but reduced refueling needs (some types can operate for up to 30 years without replenishment of uranium). The small, modular, and factory-based construction and standardization of components and systems, means reduced construction costs together with faster licensing and shorter installation times.

A further advantage of SMRs is the flexible cooling requirements and the flexibility to serve as a backup power supply [30] as they can also be employed for applications such as water desalination, which can be particularly important in islands or remote areas as well as highly interconnected smart grids operating through price-directed demand-side management and in need of reliable local power sources ensuring proper and fast islanding to prevent cascading failures [31].

Thorium dioxide and mixed fuels containing thorium can be adopted in SMRs. This is important as there is increasing interest in alternative thorium-based nuclear fuels so as to benefit from the relatively abundant thorium resources and the potential of a safer proliferation resistant fuel [32-35]. There is a regeneration of interest in thorium-based fuels and this is also reflected in the research of their physical properties [36-39]. Thorium-based fuels have advantages but require knowhow of the Th fuel cycle and hence an already developed nuclear industry. So this can be a drawback for nuclear-emerging countries such as Greece.

The difficulty to store electricity efficiently has led to the consideration of alternative routes such as hydrogen production. Hydrogen can be used in solid oxide fuel cells (SOFC) to produce electricity and power vehicles or industrial facilities. The problem with hydrogen production is that it requires energy and high temperatures. An SMR can be used in synergy with a hydrogen production facility (effectively a solid oxide electrolysis cell (SOEC)) to take advantage of the heat and the excess off-peak electricity produced by the reactor. The process in the SOEC is effectively the reverse of the SOFC and leads to the production of hydrogen. As the latter is also hard to store efficiently, chemical engineering routes can be used to convert hydrogen to syn-gas or even liquid fuel that can then be used straight on in mobile and industrial applications using existing infrastructure. Notably, the use of hydrogen apart from the difficulty to store poses safety risks as it has a wide detonation range, it is difficult to detect, and can even cause embrittlement to steel containers.

There are still some technical issues (for example, on the ceramic electrolyte membranes) that need to be overcome, but the production of syn-gas or liquid fuels taking advantage of nuclear resources is appealing, particularly if it is combined with carbon capture. That is, if the carbon required in the process is captured then there will be very little net CO_2 being produced, while the existing infrastructure will be maintained.

Workforce preparation is needed through credential-granting academic programs based on best international practices properly implemented and accredited. A properly credentialed workforce is *sine qua non* for nuclear industry and regulators, as this is an area firmly within national frames of responsibilities, and multilateral agreements for frameworks of international collaboration, fully respecting nonproliferation and safety objectives. In addition, the implementation of new licensing and siting criteria will require new expertise in nuclear safety regulatory bodies.

Last, but not least, we are aware that a “fleet” of smaller and distributed nuclear reactors is likely to present substantial problems with public acceptance. This increased risk can be important in countries with seismic areas and vulnerable to tsunamis. In addition to improvements in science education (STEM), to address the issue of public acceptance, there has to be great openness and a public dialogue that fully respects the public’s right to know and choose through democratic processes.

4. NUCLEAR IN GREECE

Having briefly presented the advantages and challenges posed by SMR technology, we now turn to consider how realistic it is for Greece to adopt SMRs, and argue that, given its historical participation in the first atomic era, it is well-positioned to participate actively in the current, new atomic era.

4.1. GRR-1: The First Research Reactor

The atomic era in Greece, as in many other developed and developing countries globally, began after Eisenhower’s “Atoms for Peace Initiative”, announced at the United Nations in December 1953 [40, 41]. According to this Initiative, first-generation nuclear facilities would be created as a result of cooperation between the United States Atomic Energy Commission (USAEC) and other national authorities on atomic energy research and power projects, on a common legal basis worldwide in the period 1950s – 1970s. In 1954, the US Congress provided the legal basis for “Atoms for Peace” by enacting the Atomic Energy Act of 1954 [42].

In the geopolitical and geoeconomic backdrop of the first decades following WWII Greece was a major part of the long-term development program “The Marshall Plan, authorizing the European Recovery Program” [43]; all energy matters in Greece, including atomic energy research, education, safety, and cutting-edge applications were part of the crucial international cooperation framework between the USA and Western Europe that led to an historically unprecedented period of peace and prosperity in the whole continent. However, Greece’s integrated energy development programme was idiosyncratic due, primarily, to the nine years that elapsed from the start of WWII in 1940 till the end of the subsequent civil war and the establishment of the Greek Public Power Corporation (PPC/DEI) in 1950 [44].

During the 1950s and early 1960s, coal was the main natural source for electricity generation; indicatively, 64% of electricity generation in 1958 was fuel by domestically available lignite [45] and this situation in the Greek energy system persisted with similar quality characteristics during the following decades, mainly due to the political / economical targeting to minimize the dependence of the energy system on oil imports (after the late 2000s, on both: oil and natural gas) and the use of indigenous sources instead. Consequently, the share of lignite (coal) in electricity generation increased from about 30% in 1973 (first oil crisis) and 47% in 1979 (second oil crisis), to 62% in 1983, 74% in 1989, 70% in 1998 and to about than 60% - 70% in 2000s (depending on the methodology). Indicatively in 2008-09 (global economic crisis), the above indicator was 53% & 56% correspondingly.

It is in general accepted that this, had a negative impact to the efficiency of the country’s energy sector and economy and specifically, during the first period we investigate in this study (until the 1980s), Greece was highly dependent on imported fuels for the overall energy mix, while generating electricity from domestically available lignites [45, 46]. Nevertheless, this was also a period of atomic and nuclear research and the quest for uranium resources for a possible nuclear power plant in Greece [47]. In accordance with the principles and the financial and technical assistance possibilities set by the international cooperation legal framework as a result of the "Atoms for Peace" US policy (1953-54), and the aspirations, the persistent focus and vision of distinguished scientists and statesmen for the modernization of the Greek economy through energy self-sufficiency and technology development [48] crucial steps were taken regarding the participation of the Greek State in the United Nations International Atomic Energy Agency (UN-IAEA). Indicatively, Greece is one of the founding members of CERN that was established in 1954 [49]. In 1954 also, the Greek Atomic Energy Commission (GAEC/EEAE) was established and given authority over nuclear safety and regulation matters [50].

The GAEC with the assistance of the US Atomic Energy Commission (US-AEC), the predecessor of the current US Department of Energy (DOE), and the Nuclear Regulatory Commission (NRC), founded the "Demokritos Nuclear Centre" in 1959, featuring a research reactor (GRR-1) and a number of supplementary laboratories [51]. Six fundamentally important years passed between the Research Agreement of GAEC with US-AEC in 1955 [52], followed by the contract signed with the American firm "AMF Atomics" for the design and construction of the first 1 MW pool Greek Research Reactor and its inauguration in 1961. GRR-1 achieved criticality for the first time on July 31st, 1961, its operation at full power began in April 1964 and in July 1971 the reactor was operated at increased power of 5 MW.

The establishment of an atomic research center in Greece contributed to the growth of scientific research in the region [53] and for decades thereafter the GRR-1 has been the main nuclear facility in Greece. It remained functional until the eve of the Athens Olympic Games in 2004. In July 2004, it was put in a state of extended shut-down. All used High Enrichment Uranium (HEU) fuel elements were returned to the USA in 2005, following the terms of fuel purchase agreement between the U.S. Department of Energy and the Greek Government. During the period 2005-2010, the reactor was shut-down for maintenance and preparation of the core conversion to Low Enrichment Uranium (LEU) [54]. Since February 2019, all LEU fuel elements have been repatriated to North America. The current license granted to GRR-1 for extended shutdown is due for renewal in October 2024 [55].

4.2. Greece's Potential Nuclear Energy Programme

Importantly, Greece is a party to the 1968 Treaty on the Non-Proliferation of nuclear weapons (NPT), which it ratified on 11 March 1970 [56] and the Additional Protocol which supplements the NPT. Civil nuclear energy was considered back in the 1960's and 1970s as one of the country's long term development program priorities [45, 48]. Several factors, such as public lectures by distinguished researchers and university professors [48], the subsequent PPC's plans and discussions to build nuclear power plants as an alternative source for electricity generation in 1963 [45], the progress in nuclear technology, the political stability after the "Junta" period and the restoration of democracy [45, 48], and the investment interest raised by the system for licensing on nuclear installations (legal framework regarding: *conditions and procedures for licensing on nuclear installation of the Public Electricity Corporation)* in 1978 [57], mobilized the scientific pool and policy makers in Greece and worldwide in investigating opportunities for designing and building a nuclear power plant (NPP) in Greece. Despite the first and second oil crises in 1973 and 1979 respectively with a strong energy impact in Greek economy [46, 58] and in spite of the government investment programme in oil & natural gas fields & PPC's lignite mines after the 1979 oil crisis, some reports and pre-feasibility and site evaluation studies were commissioned by the PPC, among them, the Ebasco's study, in order to identify potential appropriate locations for the installation of a Nuclear Plant (Table 1, Figure 2, Ref. 45 and references therein).

Table 1. Timeline of the atomic research and energy era in modern Greece.

YEAR	Milestones
1950	Establishment of the Greek Public Power Corporation (PPC/DEI), (07.08.1950)
1954	Establishment of Greek Atomic Energy Commission GAEC / EEAE (26.02.1954) CERN (Convention entered in force, 29.09.1954. Greece is one of the founder members)
1955	04.08.1955 Research Agreement between USAEC and Greece to construct a research Reactor
1961	The GRR-1 achieved criticality for the first time 31.07.1961. "Opening" of the Democritus Nuclear Centre / The inauguration of the reactor
1978	New Legislations about the establishment and operation of nuclear facilities. Conditions and procedures for licensing on nuclear installation of the Public Electricity Corporation (PPC)
1985	Administrative and operational separation of GAEC from the National Center of Scientific Research "Demokritos"
1986	Chornobyl NPP accident (26.04.86)
2004	Since July 2004, the Research Reactor is in state of extended shut-down
2011	Fukushima NPP accident (11.03.2011) New European Nuclear Safety Regulators Group [39] criteria, methodology and the timeframe for carrying out the" stress tests"
2019	GRR-1. All used LEU fuel elements have been repatriated to USA since February 2019

Figure 2. Nuclear power plants' possible locations proposed in early 1980's ([45] and references therein) in relation to the main regions with operating thermal power plants (TPP) and the Prinos oil field (P). (1) near the city of Larissa, (2) Near the village Mandudi, (3) Near the town Karystos, (4) Ilia Prefecture, (5) southwest of the city of Tripolis, (6) west of cape Maleas, (7) Near the village Archagelos. GRR-1, is the Greek Research Reactor, situated in "Demokritos' ' Nuclear Centre, Athens, WMLC - West Macedonia Lignite Centre, MLC – Megalopolis Lignite Centre.

4.3. The Consequences of Nuclear Accidents

The 26 April 1986 accident at the Chornobyl nuclear power plant in Ukraine (then USSR) had a decisive influence on the development of international nuclear law over the following two decades. In Greece, preliminary NPP construction plans froze. The then prime minister Andreas Papandreou moved on to cancel them. The abandonment of these plans boosted exploitation of Greek lignite ores (from 54% as source for electricity generation in 1980-85, lignite ores rose to 69% in 1986-91 ([45] and references therein). After the Fukushima NPP accident (11.03.2011), new criteria, methodology and the timeframe for carrying out the "stress tests" were introduced by the European Nuclear Safety Regulators Group [59].

4.4. Uranium Deposits in Greece

The research / investigations (geological surveys) for Uranium ore deposits in Greece, began in the early 1950s by American, English and French scientific teams and experts that collaborated with Greek researchers [45, 47, 48].

In the late 1970s, the Institute of Geological and Mining Research (IGME) carried out new surveys regarding categories of uranium minerals and possible mining locations in Greece. The main Uranium raw material (ore) deposits were being identified in North Greece's regions ([45, 47, 48] and references therein). The geographical sites and the quantities (of uranium mineral resources in N. Greece) are documented in [47], in "Red Books" [60], i.e., national reports, published between 1973 and 2005, and in scientific investigations [61] and references therein). The estimated Greece Uranium resources in earlier studies ([45, 47, 48, 60, 61) and in most recent estimations [62, 63] are summarized and presented in Table 2.

Table 2. Estimated Uranium Resources in Greece in Tonnes U.

Identified Recoverable Resources / (Uranium, 2009, Uranium, 2022)	**7000**
Reasonably Assured Resources (RAR)	*6000*
Inferred Resources (IR)	*1000*
Undiscovered resources (prognosticated, cost range < USD 260/KgU) [62, 63]	*6000*
Unconventional resources (phosphate rocks, reported in Red Books 1965-1993) [62]	*500*
Indicated reserves of uranium (U3O8) [61]	*1800*
Identified in situ resources (RAR + IR, cost range < USD 260/KgU) [63]	*9300*

As shown in Table 2 the current estimations in both identified recoverable resources and undiscovered resources in cost range < 260/KgU in Greece are more than 13 thousand tonnes U.

5. CONCERNS AND PROSPECTS

A main argument against the development of civil nuclear facilities in Greece has been seismic activity. It should be stressed, however, that about 20% of nuclear power stations in the world are in seismically active areas and these include facilities in the USA and Japan. Interestingly, neighboring countries with seismic activity such as Bulgaria [64] and Turkey (Akkuju NPP) operate nuclear power stations. Greece has had strict building codes for many years and was one of the first countries worldwide to enforce laws and codes for earthquake resistant buildings. The current building code, established in 2000 and informed by international and local experience, is considered one of the strictest globally and the reported damage in public buildings by earthquakes is very low. At any rate it is anticipated that there are areas in Greece with limited seismicity, where nuclear power station(s) with appropriate earthquake engineering can be built. From another viewpoint the rigorous and principled design of a nuclear structure will require substantial effort that could also have a positive impact on the future design code, thus enhancing the safety of buildings and other structures.

Another argument against the development of civil nuclear facilities in Greece has been the prospect of exploiting renewable energy sources, such as wind and solar power, which are considered safer than nuclear power, and relatively abundant in the Greek region. However, there are several points that counter this argument. One of them concerns power density [65] i.e., the average electrical power produced in one horizontal square meter of infrastructure: renewables take up a lot of space, as wind turbines must be spaced out in large areas, and likewise solar panels are meaningless if they are used only in small spaces. The power density for nuclear power is about 1000 W/m^2 compared with 2-3 W/m^2 for wind and 100 W/m^2 for solar. Another point concerns dispatchable generation capacity and reliability: nuclear reactors can generate power at a constant rate as opposed to wind farms and solar panels that rely on such volatile sources. This impacts on the stability and, consequently, safety of the power grid. Various studies have examined the potential for competitive large-scale renewable deployment and concluded that it is more difficult to accomplish than as many anticipate [66, 67]. However, the experience that has been acquired through efforts to increase the integration of renewables is valuable, should one view them as proxies for SMR integration in the grid.

The adoption of SMR in Greece will have numerous positive consequences. In conjunction with the production of electricity, SMRs may be used synergistically with electrolyzes to produce low-carbon hydrogen and hydrogen containing fuel such as methanol or ammonia. In particular, the heat and power from the SMR can be employed for the production of low-carbon hydrogen. Given SMRs flexible modular design they can be located near energy intensive industrial processes including, but not limited to, cement factories, steel mills, oil refineries, shipbuilding facilities, cable, aluminum and critical materials refineries, where emissions-free sources of hydrogen may be used to achieve carbon reduction targets in industry as well as abet the production of peak electricity with fuel cells. Presently, only very limited amounts of green hydrogen are produced and these cannot deliver the large quantities of clean hydrogen required to make a difference in transport and industrial applications. Nuclear hydrogen production taking advantage of the SMR technologies is a key component to produce low-cost hydrogen, which is critical to decarbonize and propel the economic machinery of a country. For transport applications hydrogen has advantages but it is also problematic to store (metal embrittlement, low temperatures) and handle (has a high detonation range, odorless). These problems can be overcome, however, if the net aim is not to produce hydrogen as an end product, but rather use the hydrogen produced as an intermediate step for the production of methanol, syngas and liquid fuels. This will be very beneficial environmentally, if the carbon required for these processes is via carbon capture, but also because there will be no need to change all the gas stations to hydrogen ones that will require substantial infrastructure and extensive training of the staff.

As an illustrative example, four 300 MWe SMRS can produce 10 GWh of electric energy annually, which is approximately 20% of electricity consumption in Greece. By mid-century this number can quadruple, resulting in the production of 40 GWh capable of fueling electric vehicles and, thus, replacing the current 25% of the total energy mix which is used by internal combustion engines for transportation. Additional electricity from wind, solar, biomass and hydro can result in an energy mix fully compliant with net zero targets. This can be considered a *low growth scenario*, where the economy is in steady state, that is with less than 1% average annual growth.

A more aggressive *high growth scenario* has the economy growing annually by an average of at least 3%. In this scenario, significant investment will be needed in nuclear power and the transmission/distribution system of electric power. Tripling the overall electric energy output by mid-century, that is going from approximately 50 GWh per year to 150 GWh per year, can be abetted by having at least 50% of the electric power provided by nuclear sources. In such a scenario the levelized cost of electricity is expected to be reduced to nearly 1/3 of current values extending benefits far beyond energy generation.

Another important possibility afforded by SMRs concerns the production of marine fuel. This is key for the Greek economy as one of the main pillars (arguably the strongest) of the shipping industry, which under new regulations will need to become greener. Renewable energy solutions do not have the energy density to power the fleet, whereas changing to alternative "greener" fuels will require changing the engines etc. A viable pathway may be hybrid engines burning ammonia fabricated with nuclear-produced emissions-free hydrogen.

The construction of SMRs will create numerous job opportunities, contributing to overall employment and high growth. Over 1,100,000 job-years of highly paid jobs will be added in the Greek economy under the low growth scenario. On the other hand, under the high growth scenario, which is the more likely of the two, the adoption of SMRs to fuel up to 5 GWe capacity may create in excess of 5,000,000 job-years. Nuclear power creates a substantial economic ecosystem with numerous engineering, manufacturing, logistics and service jobs [68]. As an indication of such growth prospects, consider that as early as in the 1970s Dr Karakalos conducted important radiographic work at NSCR Demokritos, which led to the uncovering of the Antikythera Mechanism gear system [69, 70, 71], opening new opportunities for archaeometry and material science. The reactor was used to perform neutron radiography, a technique that involves the use of neutrons to produce images of the internal structure of objects, through the layers of corrosion and other materials, without damaging the artifact. Neutron detector technology for materials' defect inspection (e.g. weld analysis, concrete inspection, radiation hardening) was estimated to be US$1.2 billion in 2023 and projected to US$3.8 billion in 2033.

6. CONCLUSIONS

In the present review the state of SMRs and their potential use in countries such as Greece was assessed. More than six decades after the construction of the experimental nuclear facility in Demokritos there has been no civil nuclear power station. Greece has relied heavily on domestic lignites and oil and gas imports; however, this is no longer sustainable or economically viable under decarbonization with voluntary or binding targets in almost all economic activities including, but not limited to, power generation, transportation, shipping, industry, agriculture and services.

In the present crossroads, SMRs for Greece make technical and economic sense. To keep the nuclear option open Greece will have to rapidly invest in the development of the workforce and supply chain infrastructure. It is estimated that nearly one million new nuclear technical and engineering positions will be needed globally by mid-century. Hence there is an urgent need to invest in the academic sector for engineers and technicians with nuclear credentials, as have other countries with more steady involvement in nuclear energy (for example the UK). Investments in three (3) SMR units of 1 GWe total installed capacity are expected to create approximately 200,000 man-years of employment in high-paying engineering and technical jobs. In addition, it is anticipated that the adoption of SMRs and participation in engineering workforce and supply chain development will have a very positive impact on several high-value-added sectors including domestic refining and transport, batteries, semiconductors and critical materials mining and processing. Of particular importance will be the use of low temperature heat and off-peak electricity to produce hydrogen and liquid fuels.

Nuclear power adoption will be critical in decreasing oil/gas imports and increasing energy independence for Greece. The cost of imported energy currently represents up to 10% of the GDP, and its reduction can tip the economy from recession to growth. In recent years, in the context of increasing energy independence (while at the same time contributing to the global effort for decarbonization) Greece has been investing heavily on renewables, which are volatile and harmful for grid stability. However substantial expertise has been gained from the incorporation of renewables and the consequent grid expansion required, as one might view them as proxies for SMRs.

Last, but not least, nuclear power adoption will necessitate further development of the education system, in order to prepare highly qualified human capital, and perhaps contribute to repatriate human capital, as today most of the Greek nuclear experts work abroad.

Author Contributions: The manuscript was written and edited by all authors.
Funding: This research received no external funding.
Institutional Review Board Statement: Not applicable.
Informed Consent Statement: Not applicable.
Ethics Approval: Not applicable.
Availability of Data and Materials: No data was used for the research described in the article.
Acknowledgments: Not applicable.
Conflicts of Interest: The authors declare no conflict of interest.

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ПЕРСПЕКТИВА МАЛИХ МОДУЛЬНИХ РЕАКТОРІВ: ЦІЛЬОВЕ ДОСЛІДЖЕННЯ ДЛЯ ГРЕЦІЇ

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Глобальні зусилля до декарбонізації посилюються, але перехід до зеленої економіки має високу ціну, яка, за деякими оцінками складати приблизно 3,5 трильйона доларів щорічних інвестицій, більшість з яких є початковими. Це створює навантаження на економіки, що розвиваються, які володіють викопними природними ресурсами, тому що, відмовляючись від них, вони стають все більш залежними від імпортованої енергії, що пов'язане з високою ціною, на додаток до витрат, понесених їхніми зусиллями з переходу на відновлювані джерела енергії. Ядерна технологія виробляє диспетчеризований і безперебійний водень, тепло та електроенергію, які можуть покрити вимоги до базового навантаження, і інтерес до її впровадження зростає. Малі модульні реактори (ММР, англ. SMR) пропонують ряд переваг, особливо для країн з обмеженим ядерним досвідом. Тут ми коротко оцінюємо поточний стан систем SMR і розглядаємо їхні переваги та недоліки з акцентом на їхнє потенційне впровадження в Греції. В огляді обговорюється історія, поточний стан і можливе майбутнє включення SMR в новий енергетичний комплекс Греції.

Ключові слова: *малий модульний реактор; атомна енергетика; торій*