ANALYSIS AND OPTIMIZATION OF SMALL MODULAR REACTORS' CONTRIBUTION TO THE POWER PRODUCTION OF GREECE

by

Ioannis M. KAISSAS** and *Nikolaos I. NIKOLAIDIS

Nuclear Technology Laboratory, Department of Electrical and Computer Engineering,
Aristotle University of Thessaloniki, Thessaloniki, Greece

Scientific paper
https://doi.org/10.2298/NTRP2403173K

Following the global trend for carbon-free energy production, Greece shut down most of its coal power plants and installed solar and wind systems for electricity production. Due to the time variations in the energy production of these systems, a complementary power source is needed, with the ability to change its output on demand. Small modular reactors combine zero-carbon emissions with the ability to vary the power production on demand. The objective of this study is to examine the energetic competitiveness of five appropriately selected small modular reactors compared to the total power production of coal power plants in Greece. The daily and monthly distribution of generated energy of the previous year (2023) is analyzed to demonstrate the potential operation of small modular reactors in Greece's electrical grid. The outcome addresses whether deploying a small modular reactor is energetically beneficial for Greece and indicates the number of modules required or how many small modular reactors, in combination with renewable sources, can meet the demand. The annual coal power plant production of Greece of 4.5 TWh can be substituted with one multi-module small modular reactor or a combination of them, appropriately located.

Key words: small modular reactor, electrical power in Greece, renewable energy, coal power plant, fossil fuel power plant, load following mode, base-load mode, nuclear power plant

INTRODUCTION

Current situation and challenges

Discussions about the balance between the safety issues and the profits of nuclear energy are occasionally rekindled, in countries that do not produce nuclear power yet. Such an occasion is the recent growing development of small modular reactors (SMR). The Fit-for-55 program of the European Council aims to reduce greenhouse gas emissions by 55 % by 2030 and achieve total carbon neutrality by 2050 [1]. Greece, as an EU member state, attempts to achieve that goal by decreasing the energy generated by fossil fuel power plants (FFPP) and specifically by coal power plants (CPP). Renewable sources, like solar and wind, expand rapidly but have the disadvantage of dependency upon meteorological conditions. More stable sources can be found in natural gas, oil, and nuclear power. While natural gas, oil, and nuclear fuel have become increasingly expensive, nuclear energy offers the benefits of zero-carbon emissions and longer future exploitation periods. This study analyzes the operational modes in which SMR could operate and contribute to the Greek energy system.

There are more than 98 different SMR designs under development and deployment at different stages today. Several prototypes of SMR are under construction or in commercial operation, while other designs are making significant licensing progress and are expected to be constructed as initial prototypes by 2030 [2, 3]. The reduced size of SMR resulted in many advantageous features, such as lower core inventories, enhanced flexibility, inherent safety, *etc*. As a result, the improved techno-economic characteristics of small-sized reactors stood out the overall competitiveness of this technology [4]. More information about the techno-economic trends of currently operating nuclear power systems can be found in reference [5].

The following installation challenges of SMR, mentioned in [3, 6, 7], are relevant to the Greek reality: fuel waste and spent fuel management, investment costs, complementary operation with renewables, fulfillment of sitting requirements, decommissioning plan, and safety considerations and legal framework needed for the deployment. In mainland Greece, there are two areas with installed CPP: Western Macedonia in Northern Greece and Megalopolis in the Peloponnesus, south of

* Corresponding author, e-mail: ikaissas@ece.anth.gr

Athens. These locations already have power installation for the transfer of the produced energy, making them ideal for the deployment of SMR to leverage the existing infrastructures. Further investigations must be conducted regarding the optimal deployment site, considering environmental and civil factors.

Additionally, the modularity of an SMR allows it to be factory-assembled and transported in integrated parts to a location for installation. This characteristic enables off-grid deployment in remote areas, such as islands. For instance, Crete could develop an SMR and produce energy for electricity and desalination [8].

Operating modes and fuel management

The operation of a SMR is similar to that of a conventional nuclear power plant (NPP). The operating modes are: base-load mode, primary, secondary frequency control, and load-following mode [9].

Base-load mode delivers constant power during almost the entire reactor's operational period. However, since the operation cost of an NPP includes relatively high capital costs, it makes more economic sense to operate them continuously near their maximum power capacity [9, 10].

Primary and secondary frequency controls regulate the grid frequency to the desired level (*e. g*., 50 Hz for Greece). The primary frequency control allows short-term adjustment of power production to the grid's demand in a time frame of 2-30 seconds after the deviation is detected. Typically, power modulations fall within the range of ±2 % of the nominal power. Secondary frequency control adjusts the power output setpoint to restore the grid frequency progressively to its nominal value. This procedure modifies the power level within the range of ±5 % Pn [9].

Load-following mode can adjust power production in response to variations in electricity demand. The capability of maneuvering the generated power of an SMR is determined by the manufacturers and is based on the requirements of grid operators. According to the European Utilities Requirements (EUR), a reactor must be capable of continuous operation between 50 % and 100 % of its rated power, with a power output change rate of 3-5 % of rated power per minute [9]. To adapt to the day-night alternation in electricity demand, load following is implemented with 18 hours of operation at rated power and 6 hours at low power with adjustments of 2-5 % of rated power per minute [8]. Load following mode has economic consequences related to the reduction in the load factor of the plant. However, the main problem is the thermo-mechanical stress applied to the plant during frequent and steep temperature changes due to rapid changes in power output. Therefore, load following may increase slightly the maintenance costs of the power station [9-11].

The dependence of renewable energy sources (RES) on meteorological conditions coupled with the low-efficiency factor, results in intermittent operation of those units during the day. As a result, a reliable power plant, such as an SMR, could help meet the excess power demand. This is why the concept of nuclear-renewable hybrid energy systems (NRHES), which integrates renewable sources with NPP, is becoming increasingly attractive. Load following is the main operational mode of NRHES, even though in these systems it is common to use the excess power for nuclear cogeneration [12].

The operation cycle of an SMR relies on the fuel cycle and the total fuel burn-up of the reactor. These two factors differ depending on the type of SMR [2]. The duration of the fuel cycle along with the spent fuel management plays a crucial role in the process of deployment. New technologies introduce new types of fuel. Following the Fukushima accident, the concept of accident-tolerant fuels (ATF) has been gaining momentum. The ATF is defined as any fuel that could withstand a loss-of-coolant accident (LOCA) for a longer period than the conventional fuel used in NPP [12]. The sustainability of SMR requires planning for decommissioning and managing spent fuel and waste early in their development to avoid later liabilities. Many designs propose longer operation cycles between refueling, ranging from 1.5-20 years. A spent fuel pool for temporary storage of the used fuel is included in the unit [4].

Considering the somewhat lower burn-up of some SMR, they tend to generate a bit more spent fuel than a conventional NPP. Due to the intermittent operation of an SMR, the burn-up is reduced, adding to the total spent fuel produced by the reactor [12]. Despite that, the discharged burn-up is lower for SMR and, therefore, the total spent fuel can be moderated [8]. These cons are in favor of the base-load mode operation. Many SMR developers point out the optimized design and materials that are used, that lead to lower generation of waste, like boron-free technology and longer refueling cycles [2]. The latter might affect fuel performance and other aspects, such as core maintainability, online access to service key components, and different management of the spent fuel [2]. Also, sophisticated risk assessment methods can be exploited to ensure the safety and security of radioactive waste management [13].

For LWR-SMR, various fuel cycles are adopted depending on the design. The fuel enrichment of LWR-SMR is typically low, below 5 %. Consequently, the SMR maintains low discharged burn-ups, from 2.3 to 162.4 GWd/tHM*, and achieves refueling cycles every 18, 24, or more months. The design of the SMR included provisions for storing spent fuel for up to 10 years during the reactor's lifetime [2]. Gen IV SMR use different types of fuel assemblies to achieve reactor criticality. High temperature gas-cooled SMR employ tristructural isotropic (TRISO) coated particle

*GWd/tHM means gigawat day per tonne of heavy metals fuel, which refuels during operation. The typical discharge burnup of these SMR is substantially higher, ranging between 60 to 165 GWd/tHM depending on the fuel cycle [2]. The production of TRISO elements needs to be conducted in contemporary facilities, which are specifically made for this type of production line. The reactor's burnup is a critical factor in determining the quantity of produced spent fuel. The SMR have longer fuel cycles and large spent fuel pool capacities, allowing for extended periods of operation without the immediate need for waste management consideration.

POWER PRODUCTION IN GREECE

The total distribution of power production in the country has changed drastically in recent years, with the rise of renewable energy production and the decrease in electricity production from fossil fuel power stations. As seen in tab. 1 [14], the total power demand is stable at around 50 TWh per year. From 2013 to 2023, the increment of energy production by renewable sources and the decline of energy production by coal is noticeable. Furthermore, energy production from combined cycle power plants, known for their improved efficiency, along with the increase in estimated annual imports, underscores the country's need for a more reliable mode of energy production. During the COVID-19 quarantine (2020-2021), electricity imports decreased while the overall electricity demand remained constant. During that period coal power production reduced by 4 TWh annually and stabilized at around 5 TWh per year. Conversely, the total energy production by natural gas stations gradually increased over the years. The cause of this increment was the low cost of natural gas, until the outbreak of the Russian-Ukrainian war.

In 2013, Greece primarily relied on fossil fuel power stations, including twenty-one CPP, fourteen combined circle power plants operating mainly with natural gas, and four petroleum-fueled thermal power stations. By 2021, there were ten operational CPP. These CPP were shut down over the following two years due to the construction of the Ptolemaida 5, a state-of-the-art CPP with an estimated power capacity of 616 MWe.

Table 2 shows the total power generation in GWh of every operational CPP from 2020 to 2023. The Ptolemaida 5 CPP was under construction until it began operation in December 2022. A few months before the beginning of its operation, five CPP, with a total power capacity of 1361 MWe, were gradually shut down [14]. The total power capacity of these CPP was undertaken by the Ptolemaida 5 CPP and a few new combined cycle power plants. From tab. 2 it is supposed that in the following years, the need for cleaner energy will lead to the shutdown of the CPP Ag. Dimitrios I and II and CPP Megalopolis IV [15].

To demonstrate the quantity of generated power that needs to be replaced by 2050 this study primarily relies on data from 2022 and 2023 [16]. Since 2019, RES have been integrated into the grid at a higher rate than before, leading to a significantly lower contribution from CPP in total power production. In addition, the pandemic changed slightly the power demand and therefore the total generation of energy, due to the quarantines. These facts led to the selection of the past 24 months for this study. Figure 1 shows the total monthly distribution of generated power in Greece during 2023. July has the highest electricity demand, and the greatest amount of energy is produced by renewables. The curve illustrates the total power that ideally should be replaced by a zero-emission energy source, such as NPP. Then the monthly demand by an NPP will be around 1.5-3 TWh with an average of 1.78 TWh electrical power. The minimum and maximum values are 1.34 and 2.99 TWh, respectively.

Nowadays, around 20 TWh are annually produced by Greek FFPP; from this number, only 4.5 TWh is produced from CPP, as shown in tab. 2 [16]. A total capacity power of 700 MWe (of a multi-module SMR, or several units in an SMR plant) generates 4.84 TWh electricity per year, considering their reactor operates at 80 % of its nominal power. This amount of energy is equivalent to the energy produced by CPP an-

Table 1. Total power distribution of energy from 2013 to 2023 [14]

Year	Power demand [TWh]	Renewable energy production [TWh]	Hydroelectric energy production [TWh]	Coal power production [TWh]	Natural gas energy production [TWh]	Imports [TWh]
2013	50.7	8.2	5.6	23.2	12.1	6.3
2014	50.4	8.6	3.9	22.7	6.3	13.3
2015	51.4	9.4	5.4	19.4	7.3	14.3
2016	51.2	10.2	4.8	14.9	12.5	13.5
2017	52.0	10.6	3.5	16.4	15.4	10.9
2018	51.5	11.0	5.1	14.9	14.1	11.0
2019	52.2	12.4	3.4	10.4	16.2	14.9
2020	50.1	14.8	2.9	6.9	17.8	13.2
2021	52.4	17.2	5.3	5.3	20.9	10.4
2022	50.7	19.6	4.0	5.6	17.9	11.9
2023	49.5	21.4	4.0	4.5	14.6	14.5

Table 2. Total power production from CPP in Greece [16]

Coal power plants	Power capacity [MWe]*	Power generation [GWh]			
		2020	2021	2022	2023
CPP AG. DIMITRIOS I	274	264.1	332.0	174.6	23.7
CPP AG. DIMITRIOS II	274	419.7	355.1	316.2	63.0
CPP AG. DIMITRIOS III	283	970.7	1119.5	929.1	585.6
CPP AG. DIMITRIOS IV	283	446.2	961.4	809.1	277.1
CPP AG. DIMITRIOS V	342	242.3	45.3	1510.3	1156.7
CPP AMYNTAIO I	273	333.3	0	0	0
CPP AMYNTAIO II	273	186.7	0	0	0
CPP KARDIAS III	280	528.2	333.2	0	0
CPP KARDIAS IV	280	638.9	444.2	0	0
CPP MELITIS I	289	728.7	548.6	718.3	309.6
CPP MEGALOPOLIS III	255	334.1	31.6	0	0
CPP MEGALOPOLIS IV	256	629.5	1169.8	983.6	430
CPP PTOLEMAIDAS 5	616	0	0	125.4	1657.3
Total [GWh]		5722.4	5340.789	5566.6	4503

* MWe means megawatt electrical

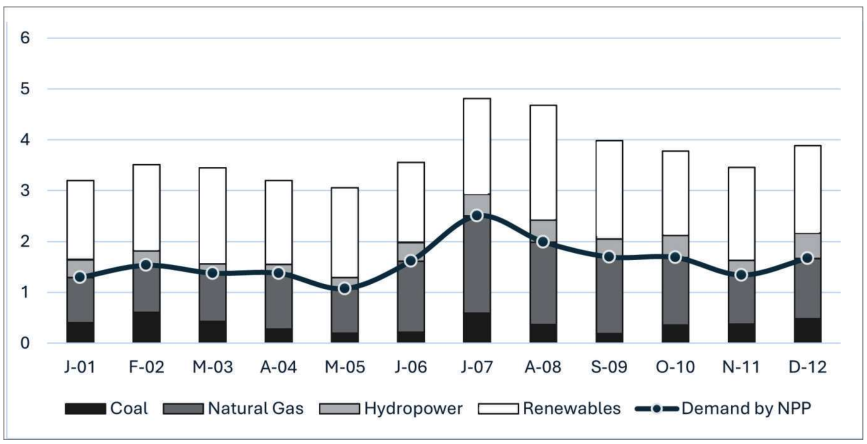

Figure 1. Monthly distribution in TWh of the total power generation in Greece during 2023 [16]

nually. One effective way to exploit nuclear power is to operate an SMR in base load mode in combination with any combined cycle stations that emit low greenhouse gases. Then the peaks of the demanded electrical power, which cannot be followed by the power production of the base load mode of the SMR, can be produced by the combined cycle stations. However, new SMR technologies can follow the load by operating in load-following mode, and this operation mode is easier for multi-module SMR.

To sum up, deploying SMR could diminish the total power produced by FFPP in Greece. For instance, a multi-module SMR with a total power capacity of 700 MWe could generate enough power to replace all currently operating CPP. Furthermore, it has the flexibility to operate alongside renewable energy systems.

TYPES OF SMALL MODULAR REACTORS

In this study, five SMR are selected that could be potentially deployed in Greece's electric grid: two multi-mode LWR-SMR, one single-unit LWR-SMR, and two advanced (Generation IV) SMR; one high-temperature gas-cooled reactor (HTGR) and one liquid metal fast reactor. The criteria for selecting these SMR are the ability to operate in load-following mode, either with single or multiple modules, enhanced passive safety systems, and a low fuel burn rate, which could lead to extended fuel circles. Additionally, the seismicity of Greece is a significant factor in determining the best areas for installation. Commercialization and licensing of the designs are the overall criteria to be considered before the selection and installation of each reactor. Table 3 contains the five types of selected SMR and some of their features. In the following section, the characteristics of these designs and the factors that lead to their selection are presented.

NUWARD (EDF)

The NUWARD reactor is an integrated PWR designed to generate 340 MWe with the cooperation of two independent reactor modules of 170 MWe each. [2]. The independent operation between the two modules offers flexibility and allows the reactor to integrate with renewable energy sources, by working in load-following mode, with greater efficiency [17].

Table 3. Types of SMR discussed in this study [2]

	Reactor	Technology developer/country	Type	Power per module [MWe]	Fuel circle [month]
1	NUWARD	EDF, France	iPWR	170	24
2	VOYGR	NuScale Power Co., USA	iPWR	77	18
3	BWRX-300	GE-Hitachi Nuclear Energy, Japan & USA	BWR	300	12-24
4	Xe-100	X-energy, LCC, USA	HTGR	82.5	Online refueling
5	ARC-100	ARC Clean Energy, Canada	SFR	100	240

The NUWARD reactor operates in base-load and load-following modes, with a range of 20-100 % of the nominal power and a rate of change of 5 % per minute. The reactor's basic grid interface complies with ENTSO-E and EUR requirements, typically at 225 kV or 400 kV and 50 Hz. The design life of the reactor is 60 years and the estimated construction time, from first concrete to criticality, is 36 months [17].

As a result, the independent operation of the two modules, along with the ability to operate at a load-following mode with a fast rate of change allows the formation of a NRHES in the electric grid of Greece. Additionally, the reactor's extensive fuel circle and provisional spent fuel management comprise two significant features for Greece, because of the time needed for the fuel recycling strategies to be developed and implemented in the country.

VOYGR (NuScale Power Co.)

The VOYGR SMR by NuScale Power Co. is a scalable arrangement of nuclear power modules that operate independently in a multi-module configuration. The NuScale power module is a small, light-water-cooled pressurized water reactor (PWR) with an electrical capacity of 77 MWe. The VOYGR plants contain a varying number of these modules, purpose-built to meet the customer's energy demands. Typically, standard plants are VOYGR-4 with four modules at 308 MWe, VOYGR-6 with six modules at 462 MWe, and VOYGR-12 with twelve modules at 924 MWe. The purpose of the design is to generate power with the flexibility to follow the grid's demand [2]. The multi-modular design allows the shutdown and activation of one or more modules during periods with greater and reduced energy production by renewable sources, respectively [4]. Each module is operated independently and is refueled by disconnecting it from the operation bay and moving it to the refueling area within the reactor pool [18]. The refueling is conducted in three parts, on a nominal 18-month refueling cycle. The estimated refueling outage time is 10 days. The refueling process does not affect the overall operation of the plant, considering that the nominal power of a module is only 77 MWe. The spent fuel pool provides storage for up to 10 years of used fuel assemblies. The plant site layout includes space allocation for dry storage of all used fuel for the 60-year design life of the plant [2].

In conclusion, the great power maneuverability of the VOYGR SMR, considering the independence of each module that could follow the grid's demand, the simultaneous operation and maintenance, and the fuel management, renders it an appealing option for Greece. The availability of the dry storage facility covering a period of 60 years is a benefit for Greece, as the solutions for the spent fuel and the radioactive waste management must be developed.

BWRX-300 (GE-Hitachi Nuclear Energy & Hitachi-GE Nuclear Energy)

The BWRX-300 reactor by GE-Hitachi Nuclear Energy and Hitachi-GE Nuclear Energy is a small, single-module, light-water-cooled BWR SMR with an electrical capacity of 270-290 MWe. Water serves as both the coolant for the core and the neutron moderator; the circulation of the primary cycle is natural, and the layout of the nuclear steam supply system follows a direct Rankine cycle [2, 19]. The lower operating pressure and the lack of a secondary cycle advance the safety and cost of the reactor [19]. The BWRX-300 could operate in base-load and load-following modes, with a power output ranging from 50-100 % of its nominal capacity [19]. Refueling outages are 10-20 days and the fuel cycle lasts 12-24 months depending on the customer's needs [2]. The relatively low peak ground acceleration of 0.3 g for the safe shutdown seismic event of the reactor allows for its deployment in earthquake-prone countries [19]. Although this feature is common in many reactors, the BWRX-300 exhibits higher seismic sensitivity.

Considering that Greece is an earthquake-prone country, the ability to disable the reactor during, even small, earthquake events is a matter of great importance. Furthermore, the broad load-following range of 50-100 % of its nominal power and the simplicity of reactivity control due to xenon stability, provide improved control of the NPP in combined operation with renewable sources. Lastly, the outstanding safety features of the BWRX-300, with five defense lines, render this reactor one of the safest commercially available [2].

Xe-100 (X-Energy, LCC)

The Xe-100 is a small, single-unit, pebble bed HTGR with an electricity capacity of 82.5 MWe designed by Xe-Energy, LCC. The design of the reactor core features around 22000 graphite pebbles, each filled with 18000 UCO TRISO-coated particles. The core's moderator is graphite, and helium is used as the heat transport fluid. At full power, approximately 173 fresh pebbles must be added and removed as spent fuel from the reactor core. This continuous (online) refueling leads to core equilibrium, with an average burn-up of 165 GWd/tHM. For further technical information on this topic, reference [20] studies the kinetic parameters of a pebble bed reactor with TRISO fuel, similar to the operating HTR-10 reactor. The reactor can operate in load-following mode, within the range of 40-100% of its nominal power. The main advantage of this type of SMR is the absence of a LOCA event. The worst accident scenario is the total loss of power accompanied by the loss of helium fluid, known as the depressurized loss of forced cooling (DLOFC). Even during a DLOFC event, the decay heat is removed via the thermal characteristics of the core and the graphite core support structures [2].

These advantages, which ensure the reactor's high safety, coupled with the commercialization of the successful Chinese HTR-PM reactor, present it as a secure solution for Greece. However, the deployment of any HTGR reactor necessitates the use of TRISO fuel particles, which must either be imported or produced domestically (in the country where the reactor is deployed). These procedures increase the operational costs.

ARC-100 (ARC Clean Energy)

The ARC-100 is a sodium-cooled fast reactor SMR with an electrical power capacity of 100 MWe utilizing metal fuel based on enriched uranium [2]. The operating pressure of this reactor is relatively low and the possibility of a LOCA event is eliminated.

The main advantages of this reactor are the affordability of this structure and the use of fast neutrons which allows the reactor to reburn its recycled burned fuel and achieve a closed fuel circle. It is estimated that the refueling outage occurs once every 20 years and has a short maintenance outage during that period [21]. The duration of the refueling, along with the safety of the fuel assembly and the use of passive safety systems leads to the selection of this SMR as a suitable option for Greece.

DEPLOYMENT OF A SMALL MODULAR REACTOR IN THE GREEK ELECTRICITY SYSTEM

The deployment of a nuclear power unit, such as an SMR, in the Greek electricity system is not new. There are plenty of challenges that need to be taken into consideration before the deployment of an SMR in the electrical grid. In the following sections, an analysis of the selected SMR is conducted, considering three specific days from the previous year: the day with the highest power demand, the day with the lowest, and one day of typical power demand in Greece.

Suitable small modular reactors

Although many factors influence the selection of the appropriate SMR, one significant factor is the ability to operate in load-following mode. Figure 2 shows the range of possible generated power of the selected designs given by the inventors. Note that NuScale provides a wide range of load-following of 0-100 %. Though this is possible, it is optimum not to decrease the generated power below 50 %, since the plant is thermo-mechanically stressed and is more attractive to maintain the primary circuit at a constant power production [6]. As a result, we assume that the range of VOYGR power plants operates between 50-100% of their nominal power.

Another important consideration is the total fuel cycle of the SMR and the duration of the refueling process. In this case, multi-module SMR are convenient because the maintenance and refueling of one module does not drastically affect the total power generated by the unit.

Considering the previous point, we can estimate the total annual power generated by each of the selected SMR, as shown in fig. 3. The diagram includes the total power generated by all CPP in the country

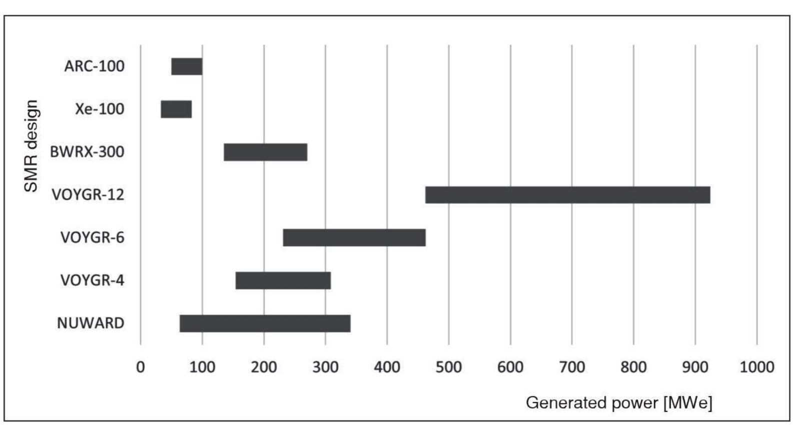

Figure 2. Range of possible generated power of the selected SMR [2]

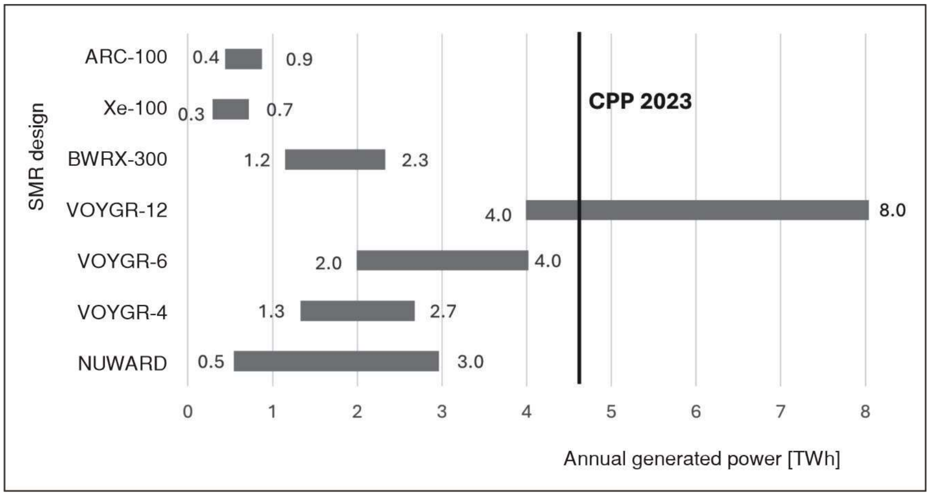

Figure 3. Range of annual generated energy by the SMR under consideration [2]

Table 4. Total power generation in load-following mode, fuel cycle, and duration of the refueling process of the selected SMR [2]

SMR	Electrical capacity [MWe]	Total LF power [MWe]		Fuel cycle [month]	Duration [d]	Core discharge burn-up [GWd/tHM]
		Min	Max			
NUWARD	2 × 170	64	340	24	20	–
VOYGR-4	4 × 77	154	308	18	10	>30
VOYGR-6	6 × 77	231	462	18	10	>30
VOYGR-12	12 × 77	462	924	18	10	>30
BWRX-300	270-290	135	270	12-24	10-20	49.5
Xe-100	82.5	33	82.5	On-line	0	163
ARC-100	100	50	100	240	–	77

during 2023. Note that a multi-module VOYGR could eventually surpass the total generation of CPP. Table 4 presents the fuel cycle and the duration of the refueling process as given by the SMR designers of the selected reactors. The NuScale power plants require refueling each module every 18 months for 10 days. During this period, the SMR operates normally with its full nominal power, minus 77 MWe. The optimal approach is to refuel and maintain each module every 4.5 months for VOYGR-4, 3 months for VOYGR-6, and every 1.5 months for VOYGR-1. This approach ensures that the total electrical capacity remains consistent throughout the year. It is evident that the highest core discharge burn-up results in the production of a greater amount of spent fuel [6]. Consequently, although the Xe-100 SMR may be the safest of the selected reactors, it has a high core discharge burn-up similar to other HTGR SMR.

Considering that the annual energy production of each SMR is three-fourths of its yearly output, the following combination of SMR can be deployed to eliminate coal power production. A secondary consideration is the location of the installations. As previously mentioned, Megalopolis' CPP, at the end of its operational life [22] produced 10 % of the total annual production of CPP. Therefore, installing a lower power production unit near the capital of Greece would be beneficial, as it would reduce energy transfer losses. Figure 4 presents the combinations of SMR that cover the recent CPP production for Greece. M values, eq. (1), are derived by subtracting three-fourths of the maximum yearly energy En_i of the i^{th} column SMR and three-fourths of the

	NUWARD	VOYGR-4	VOYGR-6	VOYGR-12	BWRX-300	Xe-100	ARC-100	(2x)BWRX	(2x)Xe	(3x)Xe	(4x)Xe	(5x)Xe	(6x)Xe	(7x)Xe	(2x)ARC	(3x)ARC	(4x)ARC	(5x)ARC
NUWARD	-0.1	-0.3	0.7	3.8	-0.5	-1.7	-1.6	1.2	-1.2	-0.7	-0.1	0.4	1.0	1.5	-1.0	-0.3	0.4	1.0
VOYGR–4		-0.5	0.5	3.5	-0.7	-1.9	-1.8	1.0	-1.4	-0.9	-0.3	0.2	0.8	1.3	-1.2	-0.5	0.1	0.8
VOYGR–6			1.5	4.5	0.3	-0.9	-0.8	2.0	-0.4	0.1	0.7	1.2	1.8	2.3	-0.2	0.5	1.1	1.8
VOYGR–12				7.6	3.3	2.1	2.2	5.0	2.6	3.2	3.7	4.2	4.8	5.3	2.8	3.5	4.2	4.8
BWRX–300					-1.0	-2.2	-2.1	0.7	-1.7	-1.1	-0.6	0.0	0.5	1.0	-1.4	-0.8	-0.1	0.5
Xe–100						-3.4	-3.3	-0.5	-2.9	-2.3	-1.8	-1.2	-0.7	-0.2	-2.6	-2.0	-1.3	-0.7
ARC–100							-3.2	-0.3	-2.8	-2.2	-1.7	-1.1	-0.6	0.0	-2.5	-1.9	-1.2	-0.6
(2x)BWRX								2.5	0.1	0.6	1.2	1.7	2.3	2.8	0.3	1.0	1.6	2.3
(2x)Xe									-2.3	-1.8	-1.2	-0.7	-0.2	0.4	-2.1	-1.4	-0.8	-0.1
(3x)Xe										-1.2	-0.7	-0.2	0.4	0.9	-1.6	-0.9	-0.2	0.4
(4x)Xe											-0.2	0.4	0.9	1.5	-1.0	-0.4	0.3	1.0
(5x)Xe												0.9	1.5	2.0	-0.5	0.2	0.8	1.5
(6x)Xe													2.0	2.5	0.1	0.7	1.4	2.0
(7x)Xe														3.1	0.6	1.3	1.9	2.6
(2x)ARC															-1.9	-1.2	-0.6	0.1
(3x)ARC																-0.6	0.1	0.8
(4x)ARC																	0.8	1.4
(5x)ARC																		2.1

Figure 4. Combinations of SMR that cover recent CPP production in Greece

maximum yearly energy En_j of the j^{th} row SMR from the total annual energy of CPP (*i. e.* 4.5 TWh). The M values close to zero indicate that the combination of the SMR i with the SMR j produces annual energy close to 4.5 TWh. The minus sign indicates the residual to reach 4.5 TWh, while the positive M expresses the oversupply above 4.5 TWh.

$$M = -\left[\left(En_{\text{CPPs}} - \frac{3}{4}En_j\right) - \frac{3}{4}En_i\right] \qquad (1)$$

In fig. 4, the light grey and the dark grey highlighted combinations indicate the residual and the oversupply to achieve 4.5 TWh, respectively. The neutral (white) combinations are the ones with residual or oversupply <|0.8| TWh, and that is an indexc of which combination of SMR can precisely cover the annual energy production by CPP (*i. e.* 4.5 TWh). The integer multiplication (*e. g.* 3x) refers to the number of SMR of the same type.

Therefore, some rational combinations of SMR, which satisfy annually the 4.5 TWh demand are:
- one ARC-100 combined with two BWRX-300
- one VOYGR-6 combined with one BWRX-300
- one Xe-100 combined with two BWRX-300
- five Xe-100 combined with one BWRX-300
- one NUWARD combined with three ARC-100
- two NUWARD
- one VOYGR-12 (with an annual oversupply of about 1.5 TWh)

To eliminate fossil fuel power production (*i. e.* CPP plus natural gas) the combination of SMR must produce 4.2 times the annual energy production by CPP (*i. e.* 19.1 TWh). Some rational combinations, which are derived using the method outlined in fig. 4, are:
- two VOYGR-12 combined with four BWRX-300
- three VOYGR-12 combined with three Xe-100
- three VOYGR-6 combined with six BWRX-300
- two VOYGR-12 combined with ten ARC-100
- four VOYGR-6 combined with four BWRX-300

Obviously, in the case of covering the whole fossil fuel power production, the combination of an NPP with SMR will be more suitable for Greece, for the generated power to be satisfied by nuclear power is high.

Power generation with an SMR on normal, lowest, and highest power demand

To demonstrate the reduction in energy production of FFPP in Greece with the addition of an SMR in the grid, three case studies are analyzed: a day with normal electricity demand, the day with the lowest electricity demand, and the day with the highest electricity demand, tab. 5. These days were selected from the previous year (2023). The type of day in these three case studies could be predicted a day before via integrated scheduling process (ISP) and the NPP could be planned to operate in load following or base-load mode.

Case Study I: Power generation with an SMR on a day with the normal demand

Before examining the upper and lower limits of power demand on the electrical grid, it is essential to analyze a day from the previous year when the power demand was relatively normal. The selection of this day was random but was made after excluding the days of higher and lower power demand in November. The selected day was Wednesday, 15 November 2023.

As we see in fig. 5, the total demand for that day was around 4 GWh, with an increment in the afternoon hours. The total generation from FFPP was stable at around 1-2 GWh with CPP producing around 300 MWe of that energy. Assuming the operation of an SMR, the total power generation from FFPP will decrease and the power production from CPP would eventually be nullified. Eliminating power generation from CPP and some of the energy generated by combined cycle power plants could also allow for the shutdown of certain units running on natural gas. It is well known that combined cycle power units have rapid insertion and extraction time from the grid.

Figure 6 shows a detailed version of the outlined part of fig. 5. As mentioned previonsly, the flexibility of combined cycle power plants, along with the fact that the operation of an NPP in base load mode is optimal, makes the mix of these two energy sources adequate for the electricity that could be produced in a day with normal demand. Finally, for this analysis, we considered that each single unit SMR operated at 80 % of its nominal

Table 5. Program of operation of selected SMR in every case; the percentage refers to the nominal power of each SMR

Day with normal demand	**00:00-23:00**		
VOYGR-12	80 % with two units off		
VOYGR-6	80 % with one unit off		
NUWARD, BWRX-300, Xe-100, ARC-100	80 %		
Day with the lowest demand	**00:00-07:00**	**08:00-16:00**	**16:00-23:00**
NUWARD, VOYGR, BWRX-300	80 %	60 %	80 %
Xe-100, ARC-100	60 %		
Day with the highest demand	**00:00-02:00**	**03:00-12:00**	**13:00-23:00**
NUWARD, VOYGR, BWRX-300	95 %	80 %	95 %
Xe-100, ARC-100	95 %		

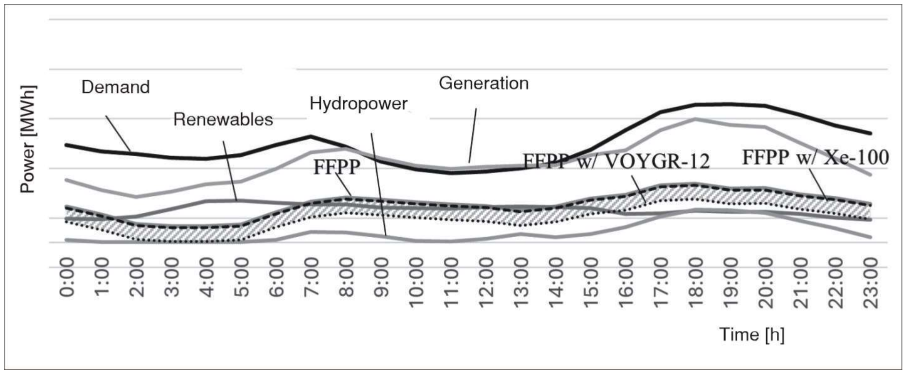

Figure 5. Day with normal demand (15.11.2023); the shaded outlined area represents the potential power generation by FFPP if one of the selected SMR were installed in the electric grid

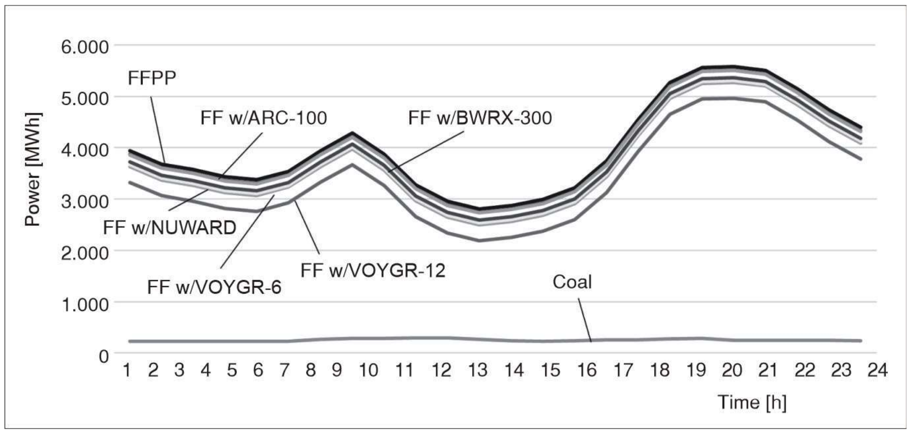

Figure 6. total fossil fuel power generation of the day with normal power demand in 2023 (15.11.2023); the most SMR could potentially surpass the total energy generated by NPP on that day

power in base load mode, except for the VOYGR multi-module SMR. For VOYGR units it was considered that one or two units were shut down for maintenance purposes.

As expected, the greater the nominal power of the SMR, the less power is generated from the CPP. The reduction of CPP's energy generation leads to the total elimination of CO_2 emissions in the environment, and probably the reduction of the total cost of electricity.

Case study II: power generation with a SMR on a day with the lowest demand

The day with the lowest demand in 2023 was Sunday, 26 March. The total demand on that day decreased rapidly from 7 a.m. to 3 p.m. Consequently, the total energy generation decreased during this period, and Greece exported some surplus energy to neighboring countries. As a result, the production from FFPP was reduced to the level of 1GWh. To demonstrate the power contribution of an operating SMR to the grid, we assume that all the SMR operate at 80 % capacity from midnight to 7 a.m., and at 60 % capacity until 4 p.m. From 4 p.m. to midnight, we assume that the SMR operates normally again at 80 % of its nominal power. The exemptions for Xe-100 and ARC-100 were also applied in this case.

Figure 7 shows the hourly total generation on that day. The shadowed, outlined area is the range of reduction of the total energy generated from FFPP if an SMR operates simultaneously. Figure 8 provides a detailed version of the previous figure, illustrating the decrease in CPP power production. Interestingly, a selected SMR could surpass the total generated energy from CPP on this day (200 MWh). Therefore, the total comparison is made with the curve of FFPP (total energy generated from CPP and combined cycle power plants). On this low-demand day, it is noticeable that the operation of SMR eliminates the usage of CPP and reduces the needed energy from combined cycle power plants.

Case study III: power generation with an SMR on a day with the greatest demand

The day with the greatest electricity demand in 2023 was Friday, 21 July 2023. On this day the total electricity demand reached 175 MWe, while the generated power in the grid was 143 MWe. The energy deficit was compensated by imports from neighboring countries. The hourly demand was around 7 MWe and gradually increased from 7-9 MWe after 18:00, resulting in greater production from FFPP throughout the day.

Assuming part of the generated energy comes from a single-module or multi-module SMR, the curve of the FFPP will decrease. The total reduction is proportional to the power production of the selected SMR. Figure 9 shows the hourly power production by each energy source and the range in which the FFPP curve would be located if one of the selected SMR were in-

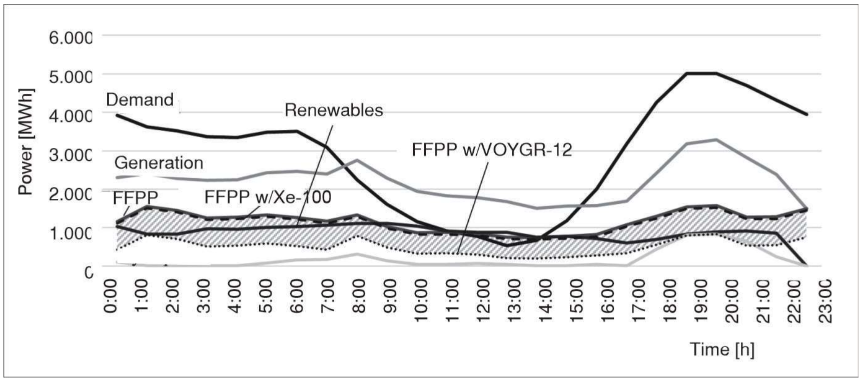

Figure 7. Day with lowest demand in 2023 (26.03.2023); the shaded outlined part indicates the potential power generation area by FFPP if one of the selected SMR were installed in the electric grid, note that from 11:00-14:00, the country exported excess generated power

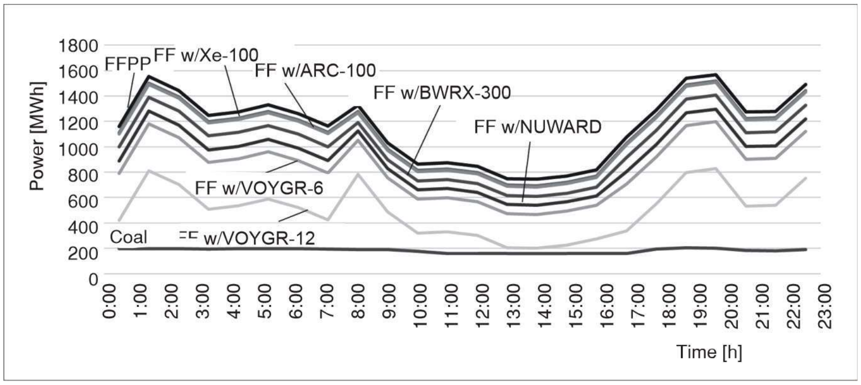

Figure 8. Total fossil fuel power generation of the day with the lowest demand in 2023 (26.03. 2023); fossil fuel power generation is the sum of combined cycle and CPP-generated power. The energy produced by any SMR will surpass the total generated power of all CPP in the country

stalled in the grid. Note that the upper and lower limits of the shaded outlined area correspond to the operation of the SMR with the lower and the higher capacity (*i. e.* Xe-100 and VOYGR-12), respectively. The goal of SMR operation in Greece is to reduce the CPP power production. Natural gas, imports, and other carbon-free sources can cover the remaining power needs. Therefore, fig. 10 shows a more detailed version of the previous diagram with FFPP replaced by CPP. On the day with the highest demand, FFPP needed to generate an exceptional amount of energy. It is noticeable that integrating coal with any SMR design would decrease the energy production of CPP and the remaining energy that must be covered by other means.

In figs. 9 and 10, all medium to high capacity SMR operate at 95 % of their nominal power from midnight to 3 a.m., then at 80 % from 3 a.m. to 1 p.m., and again at 95 % from 1 pm to midnight. The SMR do not operate at their maximum nominal power, to avoid thermo-mechanical stress on the reactor and to maintain a higher fuel efficiency of the core. The SMR produce power in load-following mode, allowing them to adapt to time-dependent deviations in demand. For the lower capacity SMR (Xe-100 and ARC-100), we assumed that they operate at base-load mode, at 95 % of their nominal power. As a result, the ISP data of this day showed a great generation of energy from renewables that could potentially fulfill the demand of the electric grid. However, the insufficient transmission and storage of this generated energy results in the exclusion of many solar and wind sources from the grid [22]. If this issue is resolved, nuclear energy and renewables can be paired to achieve total decarbonization [23]. Finally, it is apparent that each time an SMR is integrated into the grid, the curve of FFPP becomes increasingly flattened, proportionally to the total nominal power of the plant.

CONCLUSIONS

By integrating SMR with renewable energy sources and hydropower, the country could eliminate carbon emissions and achieve carbon neutrality. Combining nuclear energy and renewables is feasible, given the capability of SMR to operate in load-following mode. Operational CPP can be substituted by a limited number of one type of SMR or a combination of various SMR designs. The overall power output from FFPP needs to be addressed through a combination of different SMR.

Calculations based on data from the Independent Power Transmission Operator [16] show that the total demand on the country's grid is significant, while domestic power generation relies heavily on FFPP. The operation of an SMR, whether in load-following or base-load mode, reduces the total power production by FFPP from 55.6 % to 36.6 %, ultimately decreasing carbon emissions. Combining multiple SMR can eliminate the operation of CPP and reduce power produc-

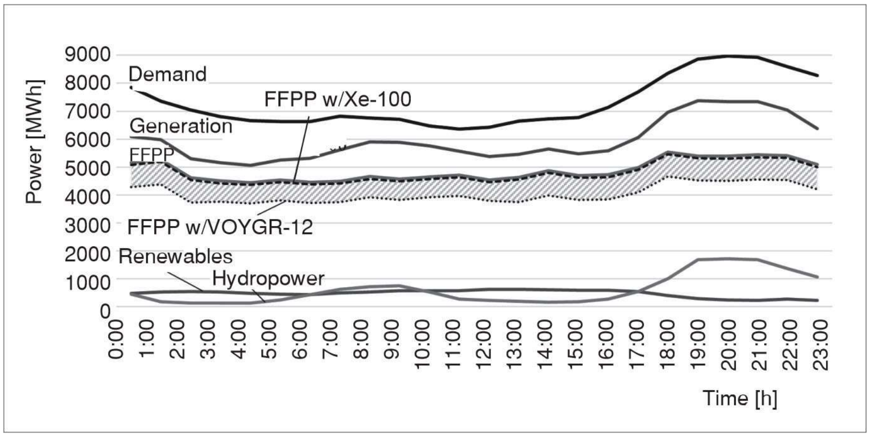

Figure 9. Day with the greatest demand in 2023 (21.07.2023). The shaded outlined area represents the potential power generation by FFPP if one of the selected SMR were installed in the electric grid

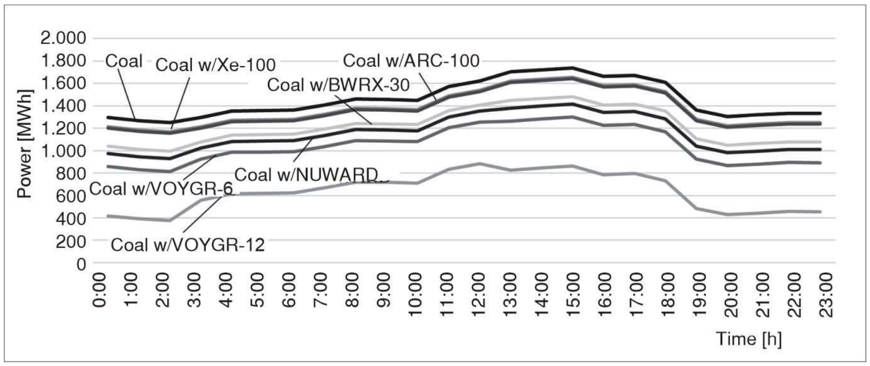

Figure 10. Day with the greatest demand in 2023 (21.07.2023). The potential power generation by CPP if one of the selected SMR were installed in the electric grid

tion from natural gas. Renewables will continue to play a significant role in balancing energy production, supported by energy storage solutions.

The combination of more than one SMR has the advantage of locating them in areas not far away from the two major consumers of Greece, *i. e*. Attica and Macedonia, which include the two biggest cities. Detailed studies should be conducted to determine whether the Megalopolis and Ptolemaida regions, which have hosted coal mines and CPP for decades, can also accommodate the SMR that might be installed in Greece.

The deployment of SMR is energetically beneficial, but long-term environmental, economic, and social aspects must be considered. Beyond power production and transfer losses, managing spent fuel and radioactive waste from fission is a critical issue that must be addressed for the successful deployment of nuclear energy in Greece.

AUTHORS' CONTRIBUTIONS

I. M. Kaissas: formulation of the problem, conceptualization, methodology, writing part of the original draft, review, and editing. N. I. Nikolaidis: conceptualization, investigation, writing original draft, editing.

ORCID NO

I. Kaissas: 0000-0002-0181-5338
N. Nikolaidis: 0009-0009-5944-0733

DISCLAIMER

The mention of names of specific companies or products (whether or not indicated as registered) does not imply any intention to infringe proprietary rights, nor should it be construed as an endorsement or recommendation by the Nuclear Technology Laboratory of Aristotle University of Thessaloniki.

REFERENCES

[1] ***, Fit for 55. Council of European Union. (2024). https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55/#:~:text=Fit%20for%2055%20refers%20to,line%20with%20the%202030%20goal Retrieved 26 August 2024
[2] ***, Advances in Small Modular Reactor Technology Developments, (2022), IAEA, Austria
[3] ***, The NEA Small Modular Reactor Dashboard: Second Edition (2024), NEA ed. OECD, pp. 11-16
[4] ***, Small Modular Reactors: Challenges and Opportunities, (2021), NEA, ed. OECD, pp. 13-25
[5] Poulopoulou, E. D., *et al*., Review of Technical-Economic Trends for Currently Operating Nuclear Power Reactors, *HNPS Advances in Nuclear Physics, 28* (2022), Oct., pp. 219-223
[6] ***, Analysis of Small Modular Reactor Concepts (SMR) – Status (2022) – Final Report ENCO-FR-(22)70 Rev 5
[7] ***, Canadian SMR Roadmap, Technology Working Group Report. (2018) Prepared by: SMR Roadmap
[8] Chalkiadakis, N., *et al*., A New Path Towards Sustainable Energy Transition: Techno-Economic Feasibility of a Complete Hybrid Small Modular Reactor/Hydrogen (SMR/H2) Energy System, *Energies, 16* (2023), 6257

[9] ***, Technical and Economic Aspects of Load Following with Nuclear Power Plants, (2011), NEA. ed. OECD. pp. 9-25
[10] Ramana, M. V., Small Modular and Advanced Nuclear Reactors: A Reality Check, IEEE Access, vol. 9, pp. 42090-42099, 2021
[11] Kerkar, N., Palilin, P., Exploitation des cœurs REP., 2008, ISBN : 978-2-86883-976-3
[12] Dong, Z., *et al*., Flexible Control of Nuclear cogeneration Plants for Balancing Intermittent Renewables, *Energy, 221* (2021), 119906
[13] Kaissas, I., *et al*., Radiological Risk Assessment Method for the Interim Storage of Radioactive Materials, *Eur. Phys. J. Spec. Top., 232* (2023), July, pp. 1523-1530
[14] ***, Heinrich Boll Stiftung, "Lignite in the Greek Energy System" https://gr.boell.org/el/o-lignitis-sto-elliniko-energeiako-systima
[15] ***, Lalela Chrisanthopoulou. "PPC: The Agios Dimitrios 1 and 2 lignite units are being withdrawn" (22 August 2024)
[16] ***, Monthly Energy Reports, IPTO/ADMIE Database, https://www.admie.gr/agora/enimerotika-deltia/miniaia-deltia-energeias
[17] ***, Status Report – NUWARDTM (EDF Lead Consortium), 2019, IAEA ARIS database. France
[18] ***, Status Report – NuScale SMR (NuScale Power, LLC), 2020, IAEA ARIS database, United States of America
[19] ***, Status Report – BWRX-300 (GE Hitachi and Hitachi GE Nuclear Energy), 2019, IAEA ARIS database. United States of America
[20] Zuhair, *et al*., Study on Kinetic Parameters of Pebble Bed Reactor with TRISO Duplex Fuel, *Nucl Technol Radiat, 38* (2023), 1, pp. 1-9
[21] ***, ARC-100 – Technical Summary. ARC Clean Energy, 2023
[22] Deligiannis, K., RES: For the First Time, Production Cut in the Interconnected Grid – No Storage, More and More "Green" Kilowatt-Hours off the System (2022) https://energypress.gr/news/ape-gia-proti-fora-perikopi-paragogis-sto-diasyndedemeno-diktyo-horis-apothikeysi-ektos
[23] Locatelli, G., *et al*., Load Following of Small Modular Reactors (SMR) by Cogeneration of Hydrogen: A Techno-Economic Analysis – *Energy, 148* (2018), pp. 494-505

Received on Septembar 9, 2024
Accepted on November 18, 2024

Јоанис М. КАИСАС, Николаос И. НИКОЛАИДИС

АНАЛИЗА И ОПТИМИЗАЦИЈА ДОПРИНОСА МАЛИХ МОДУЛАРНИХ РЕАКТОРА ПРОИЗВОДЊИ ЕЛЕКТРИЧНЕ ЕНЕРГИЈЕ У ГРЧКОЈ

Пратећи глобални тренд производње енергије без угљеника, Грчка је затворила већину својих електрана на угаљ и инсталирала соларне и ветроелектране за производњу електричне енергије. Због временских варијација у производњи енергије ових система, потребан је комплементаран извор напајања, са могућношћу промене његовог излаза на захтев. Мали модуларни реактори комбинују нулту емисију угљеника са могућношћу да варирају производњу енергије на захтев. Циљ овог рада је да се испита енергетска конкурентност пет одабраних, одговарајућих малих модуларних реактора у поређењу са укупном производњом електричне енергије термоелектрана на угаљ у Грчкој. Дневна и месечна дистрибуција произведене енергије у претходној години (2023) анализирана је како би се демонстрирао потенцијални рад малих модуларних реактора у електричној мрежи Грчке. Исход се односи на то да ли је постављање малог модуларног реактора енергетски корисно за Грчку и указује на број потребних модула или колико малих модуларних реактора, у комбинацији са обновљивим изворима, може да задовољи потражњу. Годишња производња електране на угаљ у Грчкој од 4,5 TWh може се заменити једним вишемодулним малим модуларним реактором, или њиховом комбинацијом, на одговарајућем месту.

Кључне речи: мали модуларни реактор, електрична енергија у Грчкој, обновљива енергија, електрана на угаљ, електрана на фосилна горива, режим праћења оптерећења, режим базног оптерећења, нуклеарна електрана