Review of nuclear microreactors: Status, potentialities and challenges

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Abstract

Nuclear energy is being reconsidered worldwide as a low-carbon and dispatchable energy source. Following the development of Small Modular Reactors (SMR) to reduce the capital costs and increase the safety of new nuclear power plants, microreactors are being designed by several companies. Microreactors are usually defined as SMR with a power output in the range 1-20 MW_e. They can operate as part of the electric grid, independently from the electric grid or as part of a microgrid to produce electricity and process heat. In the present paper, some microreactors at an advanced design stage are presented: eVinci^{TM}, Aurora, Holos Generators, Xe-Mobile, NuScale, Sealer, U-Battery and Micro Modular Reactor. The main applications of microreactors and the technology features are then discussed to present the main potentialities and challenges. The main advantages are the small size, the simple plant layout and the fast on-site installation. The main challenges are the limited fuel availability, the security and proliferation risk and the licensing process. Finally, an economic analysis shows that, due to an economy of scale, despite the capital cost reduction, microreactors are not cost competitive with large nuclear plants, but they are competitive with technologies with similar scale and application, such as diesel generators and renewable sources in microgrids.

Keywords: Microreactors; SMR; nuclear energy.

1 Introduction

The rising concerns about climate change and environmental pollution are forcing several Nations and Organizations to reconsider the adoption of nuclear energy as a low-carbon energy source (Kojo and Wolde-Rufael, 2010; Hiroki et al., 2010; Jungho, 2015; Bersano et al., 2020). Several projects have been launched worldwide to build new large-scale Nuclear Power Plants (NPP), such as in: Flamanville (France), Olkiluoto (Finland), Vogtle (USA), V.C. Summer (USA), Hinkley Point (UK), Barakah (UAE) and in several sites in China and Russian Federation. Some of these large projects, also called "megaprojects", showed a significant cost overrun and time delay during their construction, which in some cases caused also their failure. This was particularly evident in western countries (e.g. V.C. Summer project) while new builds e.g. in China, Russian Federation and UAE demonstrated better performances with fewer or any complications. The failure of megaprojects is often caused by overoptimistic project forecast and an underestimation of the project risks (Saunders and Townsend, 2019). Large nuclear energy projects may be fragile and susceptible to technical, operational and political risks. They have a complex supply chain and a long planning and construction time (Saunders and Townsend, 2019; Ansar and Flyvbjerg, 2016). The previous examples show that the performance and success of NPP new buildings strongly depend on each country. This peculiarity is mainly caused by the different know-how and political stability towards nuclear energy in this specific historical period.

For the mentioned reasons, nuclear sector is showing an increasing interest toward Small Modular Reactors (SMRs) as an option to generate electricity and process heat from nuclear power. SMRs are defined as advanced reactors that produce electricity up to 300 MW_e per module (Peakman et al., 2018; IAEA, 2020). The main advantages of SMRs are expected to be flexibility in the siting, improvement in safety performance and reduction of construction time. It should be however reminded that, these claimed advantages should be proven by facts since no SMR is currently under operation. In addition, there are still some technological challenges that need to be addressed: uncertainties in the development costs, lack of precise licensing requirements and economic competitiveness as cost per kW_e (Peakman et al., 2018). These challenges do not affect large scale NPP since licensing requirements are already well established, the cost per kW_e is competitive due to an economy of scale and the development cost are lower since the technology is already proven and based on a large operating experience.

Some SMRs are designed to produce a relatively low power output for industrial facilities, to power off-grid remote locations, and to be easily and quickly deployed in military installations and in locations recovering from natural disasters (National Nuclear Laboratory, 2014; INL web site). These technologies represent a subset of SMRs and they are called microreactors (IAEA, 2020). More specifically, a microreactor is a nuclear reactor with a power output usually up to 20 MW_e that can operate as part of the electric grid, independently from the electric grid or as part of a microgrid. In addition, it is suitable to generate heat for industrial facilities. This application could be hardly covered by large scale NPP since very few industrial facilities may need hundreds of MW of thermal power while many industrial plants need thermal power in the order of MW or tens of MW. During power outages, critical facilities connected to the grid, such as hospitals and water treatment plants, could continue to operate if powered by microreactors in microgrids. They represent an option for distributed power generation (Willis and Scott, 2000) in alternative to other technologies which are commonly used to provide small amount of power, such as diesel generators or small gas turbines (Peakman et al., 2018; Gabbar et al., 2020). They are designed to be portable and to produce electricity and heat without the need for continuous refueling, which is a relevant limitation of diesel generators in remote or critical areas.

The aim of the present work is to perform a review on the status of various microreactor designs (Section 2), to describe possible applications and the main technology features (Section 2 and Section 3, respectively), the key advantages (Section 4), current challenges (Section 5) and an economic overview (Section 6).

2 Overview of microreactor designs

Microreactors are currently at the earliest stage of their development. Before the deployment of a nuclear reactor, several years of planning and close coordination among reactor designers and regulators are required. For instance, the U.S. Department of Defense schedules durations and challenges for the deployment of the first microreactor before the end of 2027 (Nuclear Energy Institute, 2018). The nominal schedule has been estimated to be 7 years from license application to commercial operation and power generation. It has been highlighted that due to the singularity of this technology, challenges and risks can influence the schedule duration, thus a range of total time from 5 to 10 years has been estimated for the realization of the first microreactor. It can be stated that designs using light water cooling have a certain maturity, because they are based on technologies largely applied in conventional reactors. Instead, reactors using advanced concepts (liquid metal, molten salt, high temperature gas) will need greater efforts in the design and certification work, so the road map will be likely longer (GAO web reference).

An overview of some microreactor designs is thereafter reported and summarized in Table 1 and Table 2.

2.1 Microreactor designs

2.1.1 eVinci™

Westinghouse Electric Company is developing the eVinci™ microreactor (Arafat and Van Wyk, 2019). Its innovative design is a combination of space reactor technologies and fifty years of commercial nuclear systems design, engineering and innovation (Westinghouse web site). It has an innovative design based on a high-temperature heat pipe reactor. The electric power output can vary from 200 kW to 5 MW with more than three years without refueling. It features High-Assay Low-Enriched Uranium (HALEU) TRISO (TRi-structural ISOtropic) fuel (see Section 3.4). This technology is characterized by a simple and safe design. The core design is constituted by a solid monolithic block with tree types of channels for fuel, neutron moderators and heat pipes. The only mechanical parts are represented by reactivity control drums that surround the monolithic block. The monolithic block and the reactivity control drums are enveloped in a thick radial neutron reflector. In addition, the whole system is embedded in neutron and gamma shields. Finally, a canister encapsulates the entire core and all the barriers. Heat pipes contain a small quantity of liquid sodium to transport heat from the core to the heat exchanger. Sodium is completely enclosed in sealed pipes. In this configuration design, the heat pipes substitute the reactor coolant pump, reactor coolant system, primary coolant chemistry control and all associated auxiliary systems that characterize the traditional sodium-cooled reactor design. The reactor is thus very compact with few components. To increase reliability and safety, each fuel channel is adjacent to three heat pipes significantly enhancing efficiency and redundancy.

The advantages of eVinci™ microreactor are correlated to its technology (Westinghouse, 2019): solid core and heat pipes. The first encapsulates fuel reducing the proliferation risk and enables inherently safe core due to strong negative temperature feedback. The heat pipes technology allows to develop a compact and simple design avoiding the reactor coolant pumps and all associated auxiliary systems. Also, it can inherently adjust heat load allowing easier autonomous load following. Lastly, it guarantees a higher efficient power conversion due to its high operating temperature. The Westinghouse goal is to develop the eVinci™ microreactor in less than six years. The first step is to develop a full-scale electrical demonstration unit in order to reduce technology gaps and demonstrate manufacturability by 2020. Then, a system integral test with nuclear fuel will be constructed to demonstrate the commercial deployment of this microreactor by 2025 (Westinghouse, 2019).

2.1.2 Aurora

Oklo Inc. company is designing a new innovative microreactor called Aurora, which will produce almost 1.5MW_e (Kadak, 2017). It is designed to work autonomously for 20 years. The design is featured by a metal block containing metallic fuel in a heat pipe configuration that uses liquid sodium (Kadak, 2017). The power conversion system has not been again decided: Organic Rankine Cycle (ORC), steam or supercritical CO_2 are under consideration. The design is expected to be compact and simple. However, technical information available is insufficient in order to properly analyze this design. Aurora microreactor is designed also to burn nuclear waste from light-water reactors. Although the project is in its early stage, it has received funds to implement the design. In February 2020, the US Idaho National Laboratory announced that it will provide Oklo the access to recovered used nuclear fuel, producing HALEU for testing the Aurora concept. This decision would dramatically help the development and demonstration of the Aurora microreactor (Nuclear Engineering International web site) with HALEU Metallic Uranium-Zirconium fuel. In this respect, the Department of Energy has recently acknowledged that it is possible to produce HALEU from the fuel irradiated in the Experimental Breeder Reactor-II, as it contains high concentrations of uranium-235 (Nuclear Engineering International web site). It is hence planned the construction of an operative reactor between 2022 and 2025 (INL_web site).

2.1.3 Holos Generators

Another project is the microreactor designed by HolosGen (Figure 1). It features an innovative design that integrates mature commercial technologies with safer melt-tolerant fuels and bypasses the Balance of Plant (BoP). It is expected to operate as a closed-loop turbo-jet engine with reinforced sealed nuclear fueled cartridges. It adopts TRISO fuel, instead of the combustors (HolosGen web site) of typical turbojet engines (Filippone and Jordan, 2017). This technology has a simple design that eliminates several tubing, valves, pumps, tanks, heat exchangers. Holos primary thermodynamic conversion is envisaged as a gas Brayton cycle with Helium or Carbon Dioxide as coolant (Filippone and Jordan, 2017). Components dedicated to reject heat to the environment are coupled with a waste heat recovery and conversion system that executes an independent Rankine power cycle with an organic working fluid. ORC-Brayton coupling may increase the generator's power rating, optimize the fuel utilization and boost the thermodynamic efficiency from 45% to 60%, according to designers. After shutdown, the ORC components can continue to produce electricity by removing natural decay heat from the fuel cartridges. Under operative condition, the fuel cartridges are expected to be cooled by environmental air. Different configurations may provide scalable power from less than 1 MWe (space and highly mobile applications) to over 100 MWe (transportable and stationary applications), with near real-time load following electricity. The fuel cycle can vary from 3 to 20 years depending on the fuel enrichment (HolosGen web site). The total weight is limited to satisfy transportability requirements with the desired power rating.

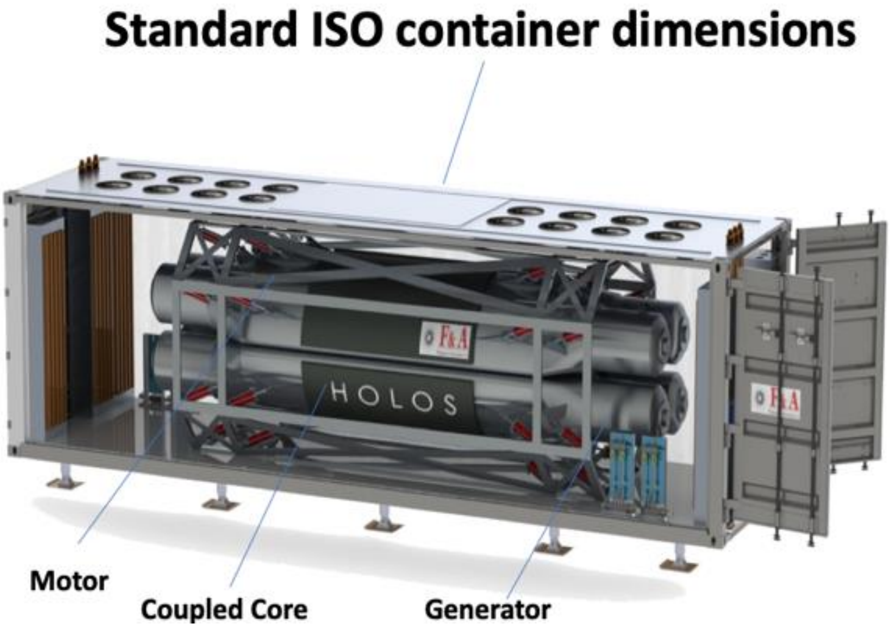

Figure 1 3D rendering of the Holos Generators microreactor (courtesy of HolosGen LLC).

2.1.4 Xe-Mobile

X-energy has developed a reactor concept the "Xe-Mobile", which is a power generation system able to provide electricity and generate power to support the need for ground, sea and air transportable small power production. The main characteristics of this project are (X-energy web site): rail, truck, and US military transport aircraft compatibility; all components can be stored in a standard container; it can operate up to 3 years without refueling; it uses TRISO fuel; it can produce at least 1 MW_e. It can run autonomously without operators on-site.

2.1.5 NuScale

NuScale Power is developing the design for a 10 to 50 MW_e micro NuScale power module and a smaller 1 to 10 MW_e heat pipe reactor (NuScale web site, Reuters Events web site). The first design is based on a technology already adopted on the SMR technology and implemented for the UAMPS project (UAMPS web site). This technology is developed for small power grids, remote village, off-grid industrial facilities (e.g. mining and military installations). Instead, the heat pipe reactor is under development to reach off-grid communities to guarantee a continuous availability of electricity, remote short-term mining installation, temporary power for humanitarian and disaster relief and for space travel. Both concepts can run for 10 or more years without refueling.

2.1.6 SEALER

SEALER is a lead-cooled microreactor developed by LeadCold (LeadCold web site). It is mainly intended to replace diesel-power in off-grid application with an electric power output of 3 MW. The core is designed to last for 30 years without refueling. Therefore, the reactors vessel can be sealed increasing the safety and reducing the proliferation risk. The long operating life is also made possible by the adoption of Alumina forming alloys to protect the fuel cladding, steam generator tubes and the primary vessel from lead corrosion. The first SEALER design is based on the use of UO_2 fuel, while the adoption of high-density fuels, in particular Uranium Nitride (UN), is being considered to improve the performances of possible future generations (Wallenius et al., 2018).

The compact design allows the transport of SEALER also by air. The decay heat can be passively removed by natural convection of the primary coolant and also by thermal radiation from the vessel to the environment. Finally, the source term in case of a complete core melt is so low that relocation of population would be required only within 1 km from the reactor (Wallenius et al., 2018).

2.1.7 U-Battery

U-Battery is developed by Urenco in an initial cooperation with University of Manchester and Technical University of Delf (U-battery web site). It is a High Temperature Gas Reactor (HTGR) cooled by Helium and moderated by Graphite, adopting TRISO fuel disposed in an annular prismatic core. The considered power size is 4 MWe (10 MW thermal). The plant is expected to operate for 30 years with a core life of 5 Effective Full-Power Years (EFPY) (IAEA, 2020). The envisaged plant layout is composed by an underground reactor cavity, spent core storage and power conversion system, while the fuel handling facility and the turbine generator are above the ground level.

Despite the use of Helium as coolant, a direct Brayton cycle is not adopted due to the significant development requirements associated with a helium turbine. The choice is to use an indirect Brayton cycle with Nitrogen as working fluid in a closed configuration (IAEA, 2020).

2.1.8 Micro Modular Reactor (MMR^{TM})

The Micro Modular Reactor (MMR^{TM}) is being developed by Ultra Safe Nuclear Corporation (Ultra Safe Nuclear Corporation web site). The core is cooled by Helium and moderated by Graphite and the power size is 5 MWe (15 MW thermal). There are two types of fuel that are being considered: TRISO and the Fully Ceramic Microencapsulated (FCM™) fuel, which is developed by Ultra Safe Nuclear Corporation itself (IAEA, 2020). FCM is composed by TRISO fuel encapsulated within a dense silicon carbide matrix, providing a fuel with high temperature stability (Ultra Safe Nuclear Corporation web site). The final fuel is in the form of cylindrical pellets, with an outer diameter of around 2 cm, stacked inside fuel channels within the Graphite blocks. The MMR is designed for 20 years of operations without the necessity of refueling, therefore the core is sealed.

The primary coolant transfers heat to a molten salt storage system, which increases the flexibility of the plant. Electricity is produced with a steam turbine Rankine cycle. Both the molten salt storage system and the steam turbine generator are located in the Adjacent Plant building, separated from the Nuclear Plant building (IAEA, 2020). An MMR demonstrative unit is planned at Chalk River (Canadian Nuclear Laboratories).

Table 1 Overview of microreactors main characteristics.

Design	Designer/Proponents (Country)	Power	Operation without refueling
eVinci™	Westinghouse Electric Company (USA)	200 kW - 5 MW electric	>3 years
Aurora	Oklo Inc. (USA)	1.5 MW electric	20 years
Holos generators	HolosGen (USA)	3-100 MW electric	3-20 years
Xe-Mobile	X-energy (USA)	1 MW electric	3 years
NuScale	NuScale Power (USA)	10-50 MW and 1-10 MW electric	>10 years
SEALER	LeadCold (Sweden)	3 MW electric	30 years
U-Battery	Urenco (United Kingdom)	4 MW electric	5 years
MMR	Ultra Safe Nuclear Corporation (USA)	5 MW electric	20 year (plant lifetime)

Table 2 Overview of microreactors main design features.

Design	Coolant	Power conversion	Fuel
eVinci™	Liquid Sodium with heat pipes	Brayton cycle	TRISO fuel
Aurora	Liquid Sodium with heat pipes	Brayton cycle	Metallic Uranium-Zirconium
Holos generators	Helium or Carbon Dioxide	Direct Brayton cycle + ORC	TRISO fuel in sealed cartridges
Xe-Mobile	Helium	Direct Brayton cycle	TRISO fuel
NuScale	Light water*	Rankine cycle*	UO_2*
SEALER	Liquid Lead	Rankine cycle	UO_2 (UN being considered for future improvements)
U-Battery	Helium	Indirect Brayton cycle with Nitrogen	TRISO fuel
MMR	Helium	Rankine cycle with molten salt storage	FCM or TRISO fuel

* (for the micro NuScale power module, very limited information available for the heat pipe configuration).

2.1.9 Other projects

In addition to the designs described in the previous sections, other projects are under development, in particular General Atomics (Nuclear Energy Institute, 2018), NuGen Engine^{TM} by NuGen (NuGen Engine web site), StarCore Nuclear (StarCore Nuclear web site), Elysium Molten Chloride Salt Fast Reactor (MCSFR) (in its reduced 20 MW_e version) (Elysium Industries web site), LFR-TL-X (Briger and Cinotti, 2019) and Molten Chloride Fast Reactor (MCFR) micro-reactor (Nuclear Energy Institute, 2019). These concepts are mainly at preliminary stages of the design process and little information is available at present. Finally, it is worth to mention the Kilopower reactor, developed by NASA specifically for space applications, adopting a Stirling power conversion cycle (Gibson et al., 2017; NASA web site).

2.2 Technology Readiness Level

The Technology Readiness Level (TRL) is an evaluation of the maturity of a technology from the initial idea to the final deployment. The idea of classifying a technology based on different steps in its design was initially developed by NASA (Straub, 2015). One of the main advantages of TRL assessment is the capability of comparing the technological maturity of different technologies e.g. to prioritize investments or to understand the possible time to market. Different TRLs definitions are available from various organizations but most of them are based on a scale from 1 to 9. In this scale 1 represents the observation of basic principles for the technology, while 9 represents a technology proven in the actual operating environment.

In the present case, the TRL evaluation has been performed considering only publicly available information and adopting the criteria proposed in (U.S. Department of Energy, 2011). In particular the nine levels are defined as:

1. Basic principles observed and reported
2. Technology concept and/or application formulated
3. Analytical and experimental critical function and/or characteristic proof of concept
4. Component and/or system validation in laboratory environment
5. Laboratory scale, similar system validation in relevant environment
6. Engineering/pilot-scale, similar (prototypical) system validation in relevant environment
7. Full-scale, similar (prototypical) system demonstration in relevant environment
8. Actual system completed and qualified through test and demonstration
9. Actual system operated over the full range of expected mission conditions

The TRL evaluation results are shown in Table 3. Most of the design can be considered at TRL 4 since the conceptual design is ready and they are based on technologies that have been already proven separately (e.g. heat pipes, ORC, TRISO fuel). Aurora and MMR are moving to TRL 5 with the construction of a prototype at Idaho National Laboratory and Canadian Nuclear Laboratories, respectively. However, it should be mentioned that there is not a strong difference between TRL 5, 6 and 7 in these cases since the full-scale demonstrator is going to be built.

TRL is linked to the time needed to reach the fully operativity of the technology and make its commercial deployment possible. In the nuclear sector the time to develop a new technology (a new nuclear plant design) and to commercially exploit it is usually very long, able to last even for few decades. In the case of microreactors, the situation is similar but huge efforts are being put to shorten the time to market of this technology. Despite it is not easy to estimate the time to market for each design with the publicly available information, it is expected that some of them could be operative before the end of the current decade (Kotek, 2019; IAEA, 2020). In this framework Aurora and MMR seem to have a slight advantage since the demonstrator plants are already planned and the sites identified.

Table 3 TRL evaluation results

Design	**TRL**	**Note**
eVinci^{TM}	4	
Aurora	4	Moving to TRL 5. Accepted combined license application by the US NRC (IAEA, 2020).
Holos generators	4	
Xe-Mobile	4	
NuScale	4	For the design based on light water technology
SEALER	4	
U-Battery	4	
MMR	4	Moving to TRL 5. License submitted for demonstrative unit (IAEA, 2020).

3 Technological features

The three main technological features that must be addressed to develop these innovative designs are: the demonstration of a robust reactivity control, the effectiveness of the fuel cooling system, and the feasibility of radioactive material confinement (International Nuclear Safety Advisory Group, 1999).

3.1 Reactivity control

As far as the reactivity control is concerned, three choices can be followed to achieve high energy production within a small core (Peakman et al., 2018). In fact, it is necessary to deal with relatively higher neutron leakages with respect to larger plants due to the much smaller core. First, the flux level may be increased. This can be done choosing core and coolant materials with low absorption cross sections in the neutron spectrum and/or introducing neutron multipliers (i.e. beryllium compounds (Tomberlin, 2004; Hernández and Pereslavtsev, 2018). However, as the flux increases, the irradiation damage in the core increases as well. Furthermore, implementation of neutron multipliers is an additional cost for the reactor (Zuckerman et al., 1981). Second, the fissile concentration may be increased. This can be done by choosing compounds with the highest percentage of uranium in the fuel and with high U-235 enrichment ratios, such as HALEU fuel. The downside of the higher enrichment is the cost increase and the risk of a plutonium rich core (Peakman et al., 2018), which should be avoided for proliferation related risk reasons. Third, the neutron energy spectrum should be able to favor the thermal end of the spectrum in order to maximize the probability of fissions. This can be done by applying an effective neutron moderator such as water, heavy water or graphite.

Hence, taking into account the necessity of core compactness, it is required to find a good tradeoff and to optimize all the three aspects here discussed, considering especially safety, proliferation and cost-effectiveness. Table 4 shows the spectrum and enrichment of the microreactors under consideration.

Table 4 Core design choices

Design	**Spectrum**	**Fuel enrichment**
eVinci™	Thermal	5-19.75%
Aurora	Fast	<20%
Holos generators	Thermal	8-15%
Xe-Mobile	Thermal	<20%
NuScale	Thermal	<20%
SEALER	Fast	19.75%
U-Battery	Thermal	<20%
MMR	Thermal	19.75%

3.2 Coolant choice

The coolant choice is fundamental because it influences the heat removal. The main features of a coolant should be: high volumetric heat capacity, no phase change during normal and accidental conditions (unless water boiling is desired for a direct Rankine cycle), low neutron absorption, possibly low pressure at operational temperatures, limited activation in presence of neutrons, chemical compatibility with core and structural materials, good thermal conductivity.

Peakman et al. (2018) made a detailed analysis on the possible coolant options grouping them. From this analysis, the most suitable coolants in terms of high-power density, high heat capacity, no phase change and low pressure, passive decay heat removal capability resulted to be molten salts, sodium and lead-based coolants. Molten salts have the advantages of natural convection cooling, to reach high temperature difference across core regions, high volumetric heat capacities. Whereas, corrosion behavior and high melting point are the major issues. Sodium advantages are its existing technical know-how, low melting point, possibility to reach high temperature difference across core regions, possibility to use electromagnetic pumps or natural circulation cooling to reduce reactor volume. However, the challenges of sodium are the limited possibility to adjust the flow rate to improve natural circulation, and its chemical reactivity with water and air. Lead-based coolants advantages are natural convection cooling, possibility to increase flow areas, high thermal inertia due to high boiling point, high volumetric hear capacity. Concerning the drawbacks of lead-based coolants, they have high melting point, corrosive nature, and production of volatile polonium compounds.

The power conversion of microreactors is in most of the designs based on a Brayton cycle (Rao et al., 2020) adopting an intermediate heat exchanger. It should be highlighted that in some microreactor designs the heat transport from the core to the intermediate heat exchanger is achieved by heat pipes, marking a strong difference with current and advanced large nuclear plants (Hu et al., 2019; Martineau, 2019; Grabaskas, 2019).

3.3 Confinement of radioactive materials

As far as the confinement of radioactive materials is concerned, microreactors require simpler and cheaper barriers with respect larger reactors (Peakman et al., 2018). Such advantage is mainly due to lower source term, lower system pressure in normal conditions and reduced probability of chemical reactions. Concerning the configuration with molten salts as coolant, the dissolution of fuel into the salt arises. On one side, the benefits are due to the strong negative temperature coefficient, the high burn-up and high conversion ratio if continuous fuel clean-up is performed and the ability to achieve a redundant shutdown mechanism related to removal of fuel into subcritical tanks (Beneš and Konings, 2012). On the other side, the technology is not fully mature and the defense in depth is reduced (the loss of coolant means loss of active fuel). In addition, the initial investment and construction of an integrated system with chemical salt clean-up are considerable.

Issues may arise concerning the lack of a containment building as normally indented for large NPPs. In fact, this aspect reduces the number of barriers between the radioactive materials and the environment and poses the issue of the defense against aircraft impact, usually considered in large NPPs.

3.4 HALEU fuel

In the United States, commercial light-water reactors (LWRs) generate electricity using low-enriched uranium (LEU) fuel. Low-enriched uranium has a uranium-235 content greater than 0.7% and lower than 20%. Today's LWR fleet uses LEU with uranium-235 levels lower than 5%. Some advanced reactors and advanced LWRs are now being designed to utilize LEU with uranium-235 levels between 5% and 20%. Fuel manufactured from uranium-235 enriched to levels between 5% and 20% is referred to as HALEU fuel and can improve fuel utilization and support better overall plant economics. The HALEU fuel envisaged for microreactors is usually in metallic, ceramic or TRISO form (Rao et al., 2020).

With the development of advanced-reactor technology, both newly constructed and operating power reactors will need HALEU fuel. The U.S. nuclear fuel-cycle infrastructure has not yet been modified to provide new sources of HALEU as well as qualified packaging that enables HALEU transport (Moe, 2019). It can be assumed that commercial supply will not materialize until a microreactor market is formed.

4 Key advantages

In addition to the known low carbon dioxide emission (IPCC, 2014), from the previous analysis emerges that the main advantages of microreactors are small size, simple plant layout and fast on-site installation. The present section will provide an overview of these features.

4.1 Small size

Microreactors technology can support different market opportunities both for stationary and portable applications (Caponiti et al., 2020). Concerning the stationary application, they can be connected to the electric grid, operate in standalone mode or as part of a microgrid to generate about 1-20 MW_e. Microreactors are mainly conceived to provide process heat for industrial applications, power remote villages where the electric grid is not available or for defense installations with reliable heat and power. As portable application, microreactors can represent an option to restore power quickly in areas damaged by natural disaster (e.g. after a tsunami, a hurricane or an earthquake) or for humanitarian relief, for example to support hospitals, or water supply to the local communities.

Due to their small size, the large majority of the components could be factory-assembled. This condition can increase the production rate of the reactor components, reduce the capital cost, and lower the time for the on-site installation, eliminating some issues typical of megaprojects. Another option under investigation is the modularization of microreactor units to further facilitate factory fabrication approaches (Moe, 2019).

Another advantage related to the small size and low power is the possible reduction of the Exclusion Area (EA) and Emergency Planning Zone (EPZ). This is already under consideration for SMRs in comparison to large-scale NPP (Almalki et al., 2019; Hummel et al., 2020) and a similar decision is likely to be taken also for microreactors due to the further reduced size (Christensen et al., 2020; Owusu et al., 2018).

To summarize, microreactors can operate where large reactors cannot. They represent an alternative choice when a clean energy source with moderate cost is needed instead of a large reactor.

4.2 Simple plant layout

Microreactors are featured by a simple plant layout that requires few components, such as in the heat pipes configurations. For example, the heat pipes technology allows to develop a compact and simple plant layout avoiding the reactor coolant pumps and all associated auxiliary systems. The heat load can be adjusted allowing easier autonomous load following and a higher efficiency power conversion can be achieved due to its high operating temperature. Some designs adopt passive safety systems, which prevent the risk of core overheating or meltdown. For instance, Peakman at al. (2018) studied a simple natural convection loop with a hot leg containing the reactor core near its base and a cold leg containing the main heat exchanger at its top.

Moreover, different microreactor designs implement a long core life able to operate without refueling for 10 years or more. In this way, the probability of accidents related to fuel handling and movement is reduced and, ideally, the capacity factor is increased. The combination of all these characteristics makes it possible to design semiautonomous operations and self-response plants within a robust, well-defined safety envelope. In addition, some microreactor designs require few workers on-site to support operations. For the module maintenance it is taken into account the possibility to perform periodic transport back to a factory for inspection and refurbishment (Moe, 2019).

4.3 Fast on-site installation

Microreactors can be connected and can generate power within a few days, which is an impressive reduction of deployment time with respect to large NPPs that usually need years. In addition, they can be easily and quickly removed from the site and exchanged with a new one or transported to another site. This feature is convenient to reduce the installation time and cost, which is significant for large NPPs. Furthermore, it makes microreactors unique for the possibility of deploying them to restore power in case of natural disasters or system blackouts.

Many microreactors are designed to fit in standard ISO (International Standards Organization) containers. This allows an easier transportability by rail, trucks, ships and even cargo aircraft. The ease of deployment of fueled microreactors from the factory to the operation site poses also some issues related to the regulations during the transportation phase (see Section 5.3).

5 Challenges

In addition to the advantages of microreactors some challenges are needed to be addressed. The most concerning are the current limited HALEU fuel availability, the higher security and proliferation risk compared to large NPPs and the licensing requirements not yet ready for microreactors. The present section will provide an overview of these features.

5.1 Limited fuel availability

The existing NPPs run with uranium-235 enriched usually up to 5%. Nonetheless, higher enrichment is required in order to achieve smaller size with a higher power to volume ratio and longer refueling period. This can be obtained by the adoption of HALEU fuel, which could reach an enrichment between 5% and 20%. It is also expected that HALEU will make it possible to optimize the system for longer lifetimes of the core and to increase efficiency and better fuel utilization. However, it is not currently available on large scale. Hence, in the U.S. Department of Energy supports the research in the development of fuel and demonstration of microreactor technology. For example, adopting the EBR-II irradiated fuel, it is possible to produce HALEU fuel for demonstration and testing purposes, as it contains high concentration of uranium-235 (Nuclear Engineering International web site).

5.2 Security and proliferation risk

Some microreactors configurations are expected to use HALEU fuels. This represents an increased risk in security and proliferation aspects with respect to the traditional nuclear power plants. Indeed, the use of HALEU or higher enriched fuel makes it more attractive for weapon program because the work necessary to realize a weapons-grade uranium is reduced.

Additionally, if microreactor technology will succeed on a large-scale market several units could be deployed worldwide and in remote locations. The number of microreactors could be potentially much higher than the number of large-scale NPPs, making the control of each unit much more complex. It is likely that the control area for a microreactor will be much smaller than the one of a large NPP and the security measures might be lower too. Therefore, the thread of potential theft of radioactive material may increase. Finally, the lack of a containment building as normally intended for large NPPs poses the issue of how to deal with aircraft impact.

5.3 Licensing

Microreactors are expected to be designed, manufactured, owned and operated with equipment and services that produce energy and power for specific applications, as explained before. Particular attention to the operational settings of microreactors is hence fundamental to identify the regulatory authority. In particular, new regulations or modification to the existing ones could be required for the licensing process and this represents a time delay to obtain design certification and to realize the microreactor (Moe, 2019).

For instance, regulations for large NPP define the presence of workers in the control room. If a microreactor is designed to allow remote control and have workers off-site, modification to the regulations could be needed. Concerning the movement of fueled reactor-modules to and from dispersed use sites, additional regulations will be required. In fact, current safety assessment methodologies or acceptance criteria have not been considered to guarantee the safety of fueled microreactor modules during transport and module mobilization/demobilization at very remote sites. Three main challenges may be identified concerning the licensing. First, the microreactor may be built and assembled at the reactor manufacturing facility, and then shipped to the selected site. In this way, the fuel will need to be shipped to the plant manufacturing facility and loaded into the reactor at this facility. It is thus necessary to design fuel shipping containers to locate the entire reactor. Second, the microreactor must be transported from the manufacturing facility to the selected site and it must be considered the possibility of return to the factory. In these situations, the fuel must remain contained into the reactor module to facilitate the movement. Third, microreactors can be conceived as temporary or semi-permanent installations. A versatile and robust means for site characterization, environmental assessment, scalable emergency preparedness, etc. must therefore be studied.

6 Economics

Micro-reactors are an emerging nuclear technology aimed at energy applications. Microreactors are well suited to address energy needs in several markets, while customer interest in this innovative technology is growing rapidly.

The economic analysis here reported represents a preliminary evaluation based on general assumptions with respect to the available information on the microreactor designs. It is focused on stationary microreactors and does not consider the economics of mobile microreactors which could be used for military application as well as for marine propulsion (FORBES web site).

Nuclear Energy Institute (2019) developed an economic analysis to calculate the Levelized Cost of Electricity (LCOE) to estimate the cost of generating electricity from a microreactor. The analysis reported takes as reference two-unit 5 MWe microreactor plant, for a total capacity of 10 MWe, and it assumes an operational life of 40 years with refueling or reactor core replacement every 10 years. In addition, it is supposed that the early microreactors will be located near existing large power plants, thus the microreactors would be able to maintain a capacity factor of 95%. In fact, in a microgrid, the microreactor may not constantly operate at maximum output. In this analysis, the site engineering and the licensing costs are included in the capital costs. In Table 5, the input data assumed to perform the economic analysis are reported.

Table 5 Selected input data to perform economic analysis (Nuclear Energy Institute, 2019).

	Nominal	**Range**
Reactor size [MW_e]	5	1 to 10
Number of co-located reactors	2	1 to 4
Plant life [years]	40	10 to 60
Core life [years]	10	5 to 20
Capacity factor	95%	45% to 95%

The costs are also influenced by factors related to the deployment condition (transport accessibility, weather, climate, labor conditions), and factors related to the microreactor designs (technology, balance of plant design). The type of organization that owns the microreactors (private or public) and the availability of loan guarantees also influence the capital cost. The need for additional transmission or distribution infrastructure is not considered in this analysis, because they will be necessary also to locate other generation technologies.

Under these assumptions, the estimated LCOE is between 0.14 $/kWh and 0.41 $/kWh. In particular, the LCOE for investor-owned is expected to be between 0.21 $/kWh and 0.41 $/kWh and between 0.17 $/kWh and 0.34$/kWh without and with loan guarantees, respectively. However, in case of public-owned the expected ranges are from 0.15 $/kWh to 0.30 $/kWh, and from 0.14 $/kWh to 0.28 $/kWh without and with loan guarantees, respectively.

The LCOE costs for the first microreactor reported are referred to a public-owned utility without loan guarantees, which would be similar for an investor-owned utility with loan guarantees. The estimated costs shown in Table 6 are based on information provided by several microreactor developers.

Table 6 Reference input cost to estimate the LCOE (Nuclear Energy Institute, 2019).

	Nominal	**Range**
Overnight capital cost [$/kW$_e$]	15000	10000 to 20000
Fixed operation and maintenance costs [$/kW$_e$·y]	350	250 to 450
Fuel cost* [$/kW$_e$]	10	6 to 14
Decommissioning [$/kW$_e$]	5	3 to 7
Cost for refuelling**	$20 million	$13 million to $27 million

* including used fuel management

** including transport and installation

In Figure 2, the sensitivity of the estimated LCOE to cost-drivers (reactor size, capital cost, number of reactors, fixed operation and maintenance cost) is reported. The main impact on the LCOE is represented by the reactor size and the capital cost, as expected. The core life, the fuel costs and decommissioning cost have a relatively little impact on LCOE (around 5% each), as shown by the data reported in Table 6.

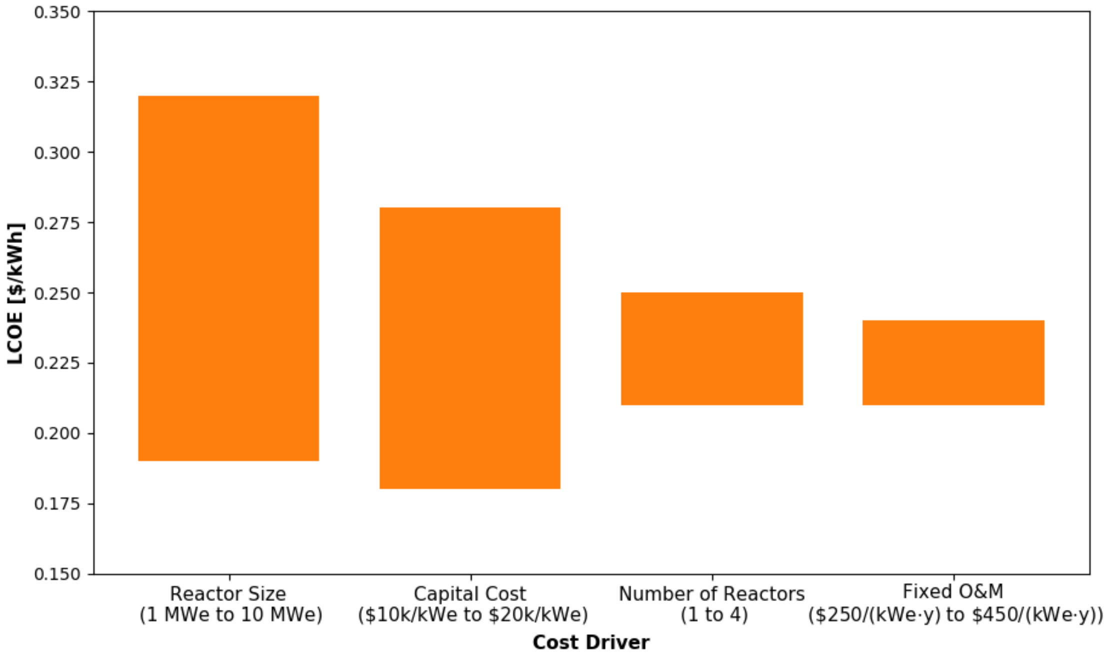

Figure 2 Sensitivity of the estimated LCOE to cost-drivers (Nuclear Energy Institute, 2019).

An important parameter which influences the cost is the plant life. Figure 3 presents the estimated LCOE of the first microreactor as function of the plant life. As expected, the cost should decrease with longer plant life. In addition, it can be state that the higher cost reduction has been evaluated between a plant life of 10 years and 20-years. From a plant life of 30 years to 60 years, the average LCOE is almost constant and around 0.22$/kWh.

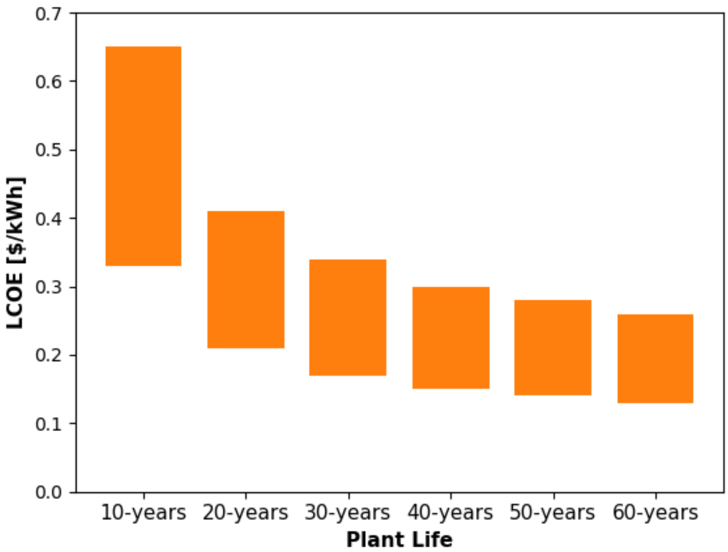

Figure 3 Estimated LCOE of the first microreactor based on plant life (Nuclear Energy Institute, 2019).

Another factor considered in the NEI analysis (2019) is the capacity factor. A range from 45% to 95% has been assumed, in fact it is considered that microreactors may not constantly operate at their maximum output. The analysis identified that the LCOE roughly doubles at half the output (with a nominal LCOE of 0.46 $/kWh for a capacity factor of 45%, and 0.23 $/kWh for a capacity factor of 95%). This result is consistent with a technology featured by very low variable operating cost respect to the fixed costs.

The cost can be reduced through the lessons learned from previous deployments. Microreactors are expected to learn by manufactured products due to their small size and factory fabrication, such as the aerospace, shipbuilding and automotive industries, which have a learning rate of 15% to 20% (EPA, 2016; Strategos, 2014). The analysis for a learning rate of 15% shows a capital cost for 1 reactor of 10000 $/kWh. A significant reduction around the half capital cost for 10 microreactors deployed has been estimated, then a slightly reduction has been evaluated reaching almost 4000 $/kWh for 50 microreactors deployed. Concerning the fuel costs, it could be reduced as more units are produced since many designs will be using novel fuel, today not largely produced. The reduction of few cents per kWh is expected for the operation and maintenance. It important to state that the exact learning rate is strictly correlated to the specific microreactor design.

In addition, in view of the commercialization of microreactors, it is important to evaluate their economics and cost competitiveness in comparison to other technologies actually used in remote areas. In this context, microreactors should be compared mainly with Diesel generators having a similar size, which now cover the applications envisaged for microreactors. Considering the capital cost, diesel generators seem to be highly advantaged with respect microreactors. Indeed, diesel generators are expected to have a capital cost of about 200-2000 $/kWe (Oulis Rousis et al., 2018; Oladokun et al., 2015), while microreactors about 5000-20000 $/kWe. Nonetheless, because of the necessity of continuous fuel supply in diesel generators, microreactors cost of electricity is still expected to be competitive on the long term. Figure 4 shows a comparison of the electricity generation cost between Diesel generators (0.15 $/kWh and 0.60 $/kWh) and microreactors (0.14 $/kWh and 0.41 $/kWh). The generation cost is similar with the Diesel one having a higher lower and upper bound. This is mainly due to the cost of the fuel (both of the product itself and of the transportation to remote areas). Therefore, microreactors are economically competitive with Diesel generators.

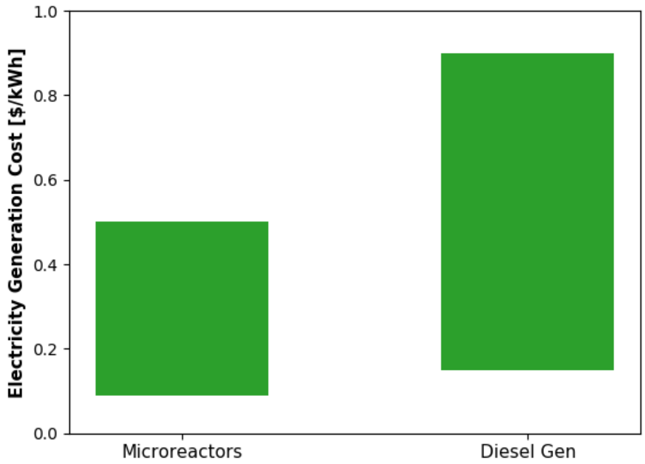

Figure 4 Electricity generation cost for Diesel generators and microreactors (Nuclear Energy Institute, 2019; Desai, 2020).

Finally, it should be mentioned that, at the expected electricity generation cost, microreactors are also competitive with other distributed renewable energy sources. Residential rooftop solar has a levelized cost between 0.16 and 0.27 $/kWh while the cost for commercial and industrial users is between 0.08 and 0.17 $/kWh (Lazard, 2018; Gilbert and Bazilian, 2020). In this respect, in microgrids renewable sources are direct competitors of microreactors on the market of remote and small communities. Likewise large NPPs, microreactors require higher initial capital costs with respect to renewables in microgrids. Indeed, they are expected to require between 5000 and 20000 $/kWe, while renewable sources in existing microgrids required about 3000-5000 $/kWe (Nuclear Energy Institute, 2019; SOLARBAY web site). According to IRENA, the current renewable in microgrids LCOE is beyond 0.40-0.80 $/kWh, where the upper bound is met especially in the case of remote full service required (i.e. for remote communities with high energy demand because of industrial and commercial requirements). However, future projections suggest that the LCOE could get as low as 0.15-0.30 $/kWh (IRENA, 2020**;** SOLARBAY web site**)** by 2035, year at which microreactors are expected to have entered the markets since few years. Figure 5 shows IRENA expected projections of LCOE for renewable microgrids for 100% renewable communities (IRENA, 2020). Similar results, or slightly more optimistic, are found in literature (Bracco et al., 2019; Lotfi and Amin, 2016).

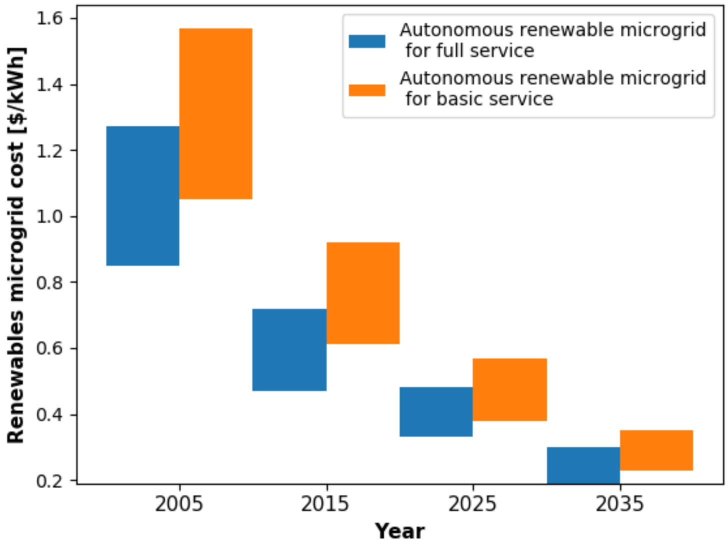

Figure 5 LCOE of renewable microgrids projections for 100% renewable energy community (IRENA, 2016).

In any case, it is important to acknowledge that most of the studies are carried out considering backups of energy storages and fossil fuel generators. In fact, according to IRENA, the actual minimum of the microgrid LCOE is met when renewables provide just about 60% of the total energy supply, leaving the rest to a diesel generator. This means that the microgrid is actually not exempt from emissions and fully autonomous.

Therefore, microreactors seem to be largely competitive with current renewable microgrids electricity price. Also, according to projections, they will be still fairly competitive by the time of their commercial readiness with the advantages of being compact and carbon free.

The main aspects of microreactor technology in comparison with other competitors are summarized in Table 7. More specifically, the table compares microreactor, diesel generators and renewable source in microgrids in terms of application fields, compactness, CO_2 emissions, electricity generation costs, and capital costs. This preliminary economic analysis wants to contextualize the possible role of microreactors with comparable technologies from the same applications viewpoints.

Table 7 Comparison among microreactor technologies and diesel generators and renewable source in microgrids.

Source	Application	Compactness	CO_2 emission	Electricity generation costs	Capital cost
Microreactor	Remote areas, industrial applications, military installations, transport	Small size	Low	0.14 $/kWh and 0.41 $/kWh	5000 and 20000 $/kWe
Diesel generators	Remote areas, industrial applications, military installations, transport	Small size	Use fossil fuels	0.15 $/kWh and 0.60 $/kWh	200-2000 $/kWe
Renewable sources in microgrid	Remote areas	Need backup of energy storages and fossil fuel generators	The actual technology is not exempt from emissions due to the need of backup energy storages and fossil fuel generators	0.15-0.30 $/kWh	3000-5000 $/kWe

7 Conclusions

The increasing concerns about climate change and environmental pollution are bringing new attention to the adoption of nuclear energy as a low carbon energy source. While new large-scale projects are being built worldwide, the reduction of plant size is considered to lower the capital cost and increase the safety of nuclear installations. Among the Small Modular Reactors, a new class of reactor can be defined with a power output usually up to 20 MWe. These microreactors offer attractive features due to their small size and reduced power, which enables their adoption for purposes not applicable to large nuclear plants. Microreactors can be a standalone energy source or be integrated in a grid, they can provide electricity and process heat to industrial installations and remote communities.

Several designs are currently under development worldwide and the most advanced ones have been described in the present paper. Despite some differences, all designs share several advantages with respect large plants. In particular, the main advantages are expected to be the simple plant layout, which improves the safety, the easy deployment and fast on-site installation, which allow to use these reactors also in emergency situations. Still, some shared challenges can be identified. There is a necessity of updated and adapted licensing regulations, seeing as how they were developed for large reactors. Additionally, the limited availability of HALEU fuel and the increased security and proliferation risks need to be carefully addressed. A preliminary economic analysis is also reported underling that the cost represents an important challenge to the commercialization of microreactors. However, at the present level of knowledge the microreactors costs are comparable with that one of diesel generators and renewable source in microgrids for same applications.

In order to overcome these issues, it seems unavoidable the need for a strong cooperation among research institutions, industry and regulatory bodies. In fact, many microreactors are being developed by relatively small private companies or consortiums, which may not have the availability of resources for sustaining the design costs of a new reactor. Indeed, the cost for the design of a reactor does not linearly scale with the power. The regulatory bodies should start to adapt their guidelines for the specific case of microreactors with the purpose of reducing the licensing process time and cost. Research institutions can provide access to their experimental facility to speed up the design process, as it is already successfully ongoing in the US.

Acknowledgements

The authors gratefully acknowledge Oklo, HolosGen and NASA for the interest shown for this activity and in particular HolosGen and NASA for sharing information and graphical contents.

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