NAAREA for IAEA – Non-electric application

Abstract: NAAREA (Nuclear Abundant Affordable Resourceful Energy for All) is a French company developing a new energy solution: the XAMR® (eXtrasmall Advanced Modular Reactor), a mass-produced molten salt fast neutron microreactor. NAAREA's XAMR® will be capable of generating electricity and/or heat from long-lived spent fuel produced by current conventional reactors.
This paper aims to present how NAAREA envisions various applications for the purpose of decarbonizing human activities through its 80 megawatts thermal/ 40 megawatts electric reactor. Among these, the innovation of advanced nuclear lies in its ability to address off-grid markets, such as medium-temperature (100-400°C) and high-temperature (400-650°C) industrial processes, district heating, electro-fuel production or carbon capture technologies. Given its technological choices, NAAREA will contribute locally to the construction of hybrid energy systems capable of securing the energy supply in addition to the electricity grid. The combination of molten salt technology and the miniaturization of the solution paves the way for a true decentralization of energy supply. In particular, the use of process or waste heat is made possible by the proximity to the consumer site. Besides, MSR's high safety standards will not only help qualify XAMR for many industrial and urban markets, but also ensure its acceptance and support by society.
It should be noted that NAAREA interprets the term "non-electric application" as the deployment sectors that do not consist of using the electricity transmission network. This means that this can include processes using electricity produced for self-consumption such as desalinization by reverse osmosis or nuclear-powered datacenters.

1) Introduction – Innovation in nuclear sector as a response to the climate emergency

Energy is at the core of all development and growth. However, it is still predominantly based on fossil fuels and is the source of nearly 70% of greenhouse gas emissions, which are responsible for climate change. Driven by population and economic growth, and the rapid expansion of digital technology, energy demand is expected to skyrocket in the coming years, thereby increasing the risk of rising greenhouse gas emissions. Without adapting the current system, energy producers and network operators will not be able to secure the supply for all stakeholders (industry, populations, public services, etc.) while meeting the stated goals of the energy transition.

The growth resulting from the Industrial Revolution has favored the development of densely urbanized areas consuming increasingly centralized energy production. However, this system has its limitations. Production locations are increasingly required to move closer to consumption sites to minimize energy losses and secure energy supply for territories facing ever-growing risks from climate, economic, social, and health challenges.

To address the challenges posed by climate change and ensure sustainable development, clean energy solutions exist. However, their large scale (conventional nuclear), dependency on energy transmission and/or distribution networks, or intermittency (renewable energies) only provide a partial solution.
Mastering decentralized, dispatchable, sustainable, and abundant energy production presents both operational and strategic benefits. It enhances sovereignty through autonomy, provides an undeniable operational advantage, serves as a vector of performance and resilience, and significantly contributes to achieving the goals of energy transition and sustainable development.

The energy of the future needs to be safe, equitable, sustainable, and decentralized. In this context, NAAREA is developing a nuclear microgenerator, called XAMR® (eXtra-small Advanced Modular Reactor).

2) Strategic choices: XAMR technology features

The XAMR® is a nuclear microreactor capable of generating electricity and/or heat from long-lived spent fuel produced by current conventional reactors. NAAREA's market options resulting in non-electrical applications can be analyzed according to three pillars: **(1) technological choices, (2) industrial approach and (3) integrated business model.**

Regarding **technological choices**, the XAMR® is a fast neutrons molten salt micro-reactor. Molten salt reactors are generally chosen for their safety profile, which, through the use of liquid fuel, opens the door to passive safety levers such as the absence of pressure or control of reactivity through the intrinsic behavior of the material in liquid form. Molten-salt reactors also allow operation at high temperatures (around 700°C), a high degree of controllability and excellent compactness. Regarding non-electric applications, it should be noted that the choice to develop this technology is also the result of a market analysis and the will to have the greatest major impact on development and environmental indicators. As such, considering that heat represents nearly half of final energy consumption[1], the choice was made to produce both electricity and heat.

The choice of fast neutrons stems from the desire to reuse spent nuclear fuel from the current nuclear fleet and improve the social acceptability and sustainability of nuclear technologies as a whole. Finally, developing a miniature reactor enables a decentralized deployment, as close as possible to the user sites, while providing the volume of energy needed for most of them. The power of the reactor (80 MWth) also makes it possible to ensure both regular and emergency cooling without water and thus improves safety functions. It also makes it possible to adopt a truly industrial approach.

This **industrial approach** consists in developing the reactor and an industrial tool adapted to series production, within a manufacturing plant, to mass-produce its XAMR®. Industrial production makes it possible to improve the reliability of production and commissioning, to be able to produce rapidly and modularly and, finally, to achieve economies of scale.

NAAREA's strategy and **business model** is to sell "energy as a service" with a performance contract. The range of services provided by NAAREA will include manufacturing, transportation, on-site delivery, implementation, connection, training, security, insurance, operations and maintenance, emergency interventions including neutralizing or deactivating XAMR®s, and end-of-life management. At the end of their lifecycle, XAMR®s will be systematically replaced and returned to the factory for regeneration (extensive maintenance and hardware modifications) before being reintroduced to the market. The fuel will be transported separately to a dedicated facility for reprocessing.

The business model also consists in offering customers access to a "thermal energy band" and enjoy the type of energy they want, flexibly over time. Energy that is not used, within the "thermal energy band", can be sold and injected to the electricity or heat networks to which it may be connected.

The energy supplied can be electricity (up to 40 MW per reactor) and heat, either high or medium-temperature, or low-temperature corresponding to the fatal part of electricity generation through the supercritical-CO_2 turbine[2]. The entire facility offers the following advantages: compactness (nuclear island fits in a 40-feet container, whole facility in one hectare), high dispatchability (from 0 to 40 MW in a few minutes), resiliency and autonomy (one charge lasts around 4 years) and modularity (the band can be increased, and more reactors can be deployed on site).

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[1] Heat, Renewables 2023, available here : https://www.iea.org/reports/renewables-2023/heat (consulted in May 2024)

[2] A patent is currently being filed. For this reason, we will not go into detail. The solution will be described in more detail if the patent is published between now and the conference in October.

3) Increasing knowledge of non-electrical applications markets: continuous learning through feasibility studies

Since the first half of 2023, NAAREA has undertaken a feasibility study program covering all economic sectors considered to be energy-sensitive. To date, 14 of the 19 sectors identified have been the subject of preliminary or detailed analysis.

This approach is based on continuous learning by proposing working hypotheses to potential clients and carrying out feasibility studies along jointly defined lines. Based on the lessons learned, NAAREA can adapt its offering/service standards to better match with market needs.

It is precisely in this context that NAAREA has expanded the potential targeted markets for heat applications. Indeed, the roadmap for the design of the XAMR® conventional island provided for the achievement of the best electrical efficiency via a supercritical CO2 turbine, i.e. about 50%. At this point of operation, the waste heat from the turbine reached a temperature of around 75°C. Several case studies have demonstrated that this temperature is the lower limit of a number of applications, such as hot water heating networks or several CCUS processes.

As a result, it was decided to lower the efficiency of the turbine from a few points, in order to produce waste heat at 100°C. This temperature level makes possible, among other things, to meet the expectations of heating networks, the desalination of seawater, CO2 capture processes, several processes in the food industry and the marginal improvement of the efficiency of electrolysers.

4) Targeted markets: focus on non-electrical applications

Some of the technological choices made by NAAREA are the direct consequence of the market analysis carried out upstream. Potential markets can be divided into three main categories:

- Sectors linked to the development of "**sustainable cities**", i.e. service activities for populations such as data centers or drinking water supply, but also district heating networks.
- Activities linked to **mobility**, whether light, through the sale of electricity on the electricity grid, or heavy, through the production of electro-fuels or direct nuclear propulsion (particularly naval).
- **Industrial** sectors, in particular heavy industry, which can be decarbonized directly by supplying heat or electricity, or indirectly by producing hydrogen or implementing carbon capture, utilization and storage technologies.

Generally speaking, NAAREA sees its business development mainly as being independent of electricity networks. Although a connection is appropriate from an economic point of view, particularly for the resale of unused electricity, NAAREA envisages deployment in a similar way to a cogeneration unit, where the local customer or customers would use both the heat and the electricity generated. Our recent studies (see previous chapter) have confirmed that the power available to customers coincides with their needs.

We can thus distinguish three types of uses that fall into the "non-electric applications" category:

1. Processes that use heat as an end-use for the user. These are mainly industrial processes, but also district heating networks.
2. Activities using heat or electricity as an intermediate energy carrier product. This category includes, for example, hydrogen production, e-fuel production and various carbon capture technologies.
3. Sectors that use electricity in a decentralized way to overcome the grid constraints, in a need of resilience and competitiveness (e.g. data centers, or production of desalinated water).

Heat as the final energy for the user

As mentioned earlier, molten salt technologies operate at around 700°C and therefore produce process heat at around 600°C. As a result, the waste heat extracted from the turbine can also be recycled, with a temperature of about 100°C. This category thus includes all users whose heat needs are below 600°C or whose feasibility of a preheating system is proven. The advantage of NAAREA is that it can offer these different types of heat with triple flexibility. Firstly, the flexibility/dispatchability of the power generated and delivered to the customer. Secondly, the flexibility between different heats and electricity generation. Thus, as part of its contract for a thermal band, a customer will be able to use high-temperature heat for its process during periods of high activity and replace it with electricity during maintenance of the industrial tool. Thirdly, flexibility in the volume of heat available on the site, through an increase in its bandwidth or the addition of new microgenerator units if the need grows persistently.

At the same time, innovative nuclear power as proposed by NAAREA makes it possible to accelerate the deployment and energy transition of district heating networks (DHNs). In Western Europe, an increasing proportion of DHNs are reducing their associated greenhouse gas emissions, mainly through the commissioning of biomass boilers. However, biomass is a good with limited availability, with competition on its production (vs. reforestation) and its societal use (vs. food production) and energy (vs. biogas production for "hard-to-abate" industries, for example).

The deployment of a micro-generator is a key opportunity to reduce the marginal operating costs of an DHN while decarbonizing the heat produced. Micro-generators have the advantage of offering better availability and resilience than renewable energies and exothermic industries, and no competition for use as for biomass. The fatal generation of heat at 100°C makes this option an excellent opportunity for the decarbonization of residential heat, which accounts for almost half of the energy needs in the building[3].

Heat and electricity as an intermediate energy carrier

Despite its ability to produce heat at high temperatures, some processes require temperatures that are too high to be decarbonized directly. Some of them can be done through the electrification of the process, such as the glass industry. Others cannot or do not wish to adapt their production tools and rely on the production of molecules offering an alternative that is not far from current practice. This is the case, for example, in the metallurgical industry with *direct reduced iron* processes, which consist in reducing iron ore with hydrogen instead of coke. The need is 55,000 tons of hydrogen per million tons of steel.

As part of the decarbonization of maritime transport and aviation, NAAREA is also studying the possibility of producing electrofuels of all types. For example, the production of e-methanol (liquid fuel for maritime transport) requires the production of carbon-free hydrogen and the adjunction of CO_2, either through biomass or through capture (direct or atmospheric). A microgenerator operating at high temperature can produce hydrogen via new high-temperature electrolysis technologies (Solid Oxide Electrolyze Cells, SOEC), and capture CO_2 by chemical absorption requiring heat at around 100°C. In this way, a 80MWth XAMR® can produce about 40,000 tons of e-methanol yearly.

Electricity produced in a decentralized way for critical uses

NAAREA is also studying the opportunity to deploy its microgenerators to players whose needs for electricity are critical, particularly from the point of view of the production tool, which must avoid an unscheduled shutdown as much as possible. This is the case, for example, of the glass industry, part of

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[3] Heating, International Energy Agency, available here: https://www.iea.org/energy-system/buildings/heating (consulted in May 2024)

which wants to implement electric electrode furnaces to replace natural gas and decarbonize their production. This is also the case for the data center sector. In addition to supplying electricity for data centers, the advantage of micronuclear lies in its highly modular aspect (in the sense that new units can be added as needed). Indeed, the data center sector does not have the same dynamic as the traditional industry, which is based on the rapid construction of a production tool sized to the long-term needs. In the case of data centers, the ramp-up is done in blocks of servers, until a maximum power level is reached, which is constrained either by the electricity supply, or by the connection to the digital network or by the available land. The use of highly modular micronuclear power makes it possible to gradually support the ramp-up of the various data center blocks, from low power (about 10 MW) to site completion (up to more than 100MW in Europe).

5) *Practical case study: the production of e-fuels by a XAMR*

Whatever the scenarios of sobriety and energy efficiency in the naval sector, the maritime transport sector must organize the energy transition strategy today in order to achieve climate neutrality around 2050, with indicative checkpoints in 2030 (-20%) and 2040 (-70%)[4]. In addition to alternative solutions, particularly sailing technologies (installation of rigid or flexible sails), operators must find new fuels to propel sea freight. Due to competition for biomass, attention is generally turning to electrofuels, both hydrogen and its derivatives such as e-ammonia, e-methane or e-methanol.

NAAREA, in collaboration with industry stakeholders, has been closely studying the feasibility of producing e-methanol using XAMR®s. Methanol is an organic compound with the formula CH3OH, i.e. an alcohol. It has an energy density of 19.9 MJ/kg and is therefore already used as an internal combustion engine fuel (mixed with conventional oil products). Methanol is produced from CO2 and hydrogen. Historically produced by catalytic hydrogenation of a syngas from natural gas or coal, e-methanol can be produced by hydrogenation of CO2.
Production processes (whether catalytic synthesis, syngas production by co-electrolysis or electro-catalysis of CO2 and water) require CO2 and H2 as raw materials. The production or capture of these two materials are considered as serious barriers to the mass production of e-methanol. Indeed, hydrogen must be produced by electrolysis of water, generating a yield loss of around 40% with current technologies, and CO2 capture also generates an energy penalty for CCUS processes and high energy consumption for *direct air capture*.

The use of a XAMR® microgenerator has several advantages to make it possible to massively produce e-methanol:
High-temperature heat production: the generation of heat at around 600°C paves the way to the production of hydrogen by high-temperature electrolysis. The high-temperature heat input leads to a significant improvement in the efficiency of electrolysers, in particular because of the reduction in thermoneutral voltage, which implies a reduction in electricity consumption for the same production. As a result, at 600°C, the energy input for the production of one kilogram of H2 decreases from about 55 kWh electric to about 39 kWh, including 30 kWh electric and 9 kWh thermal. For the same primary energy, the use of a XAMR® micro-generator allows an improvement in efficiency of 55%.

Elimination of the energy penalty for CO2 capture by using waste heat: CCUS technologies require the implementation of means to capture CO2 when they are emitted during industrial activities. This emission can be due to the combustion of hydrocarbons or due to process production such as clinker.

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[4] 2023 IMO Strategy, International Maritime Organization, 2023, available here : https://www.imo.org/en/MediaCentre/HotTopics/Pages/Cutting-GHG-emissions.aspx

CCUS technologies impose a technological penalty, i.e. the need is greater than the source of waste energy available at the transmission site. For example, the most advanced technology is the pre-combustion absorption of CO2 by aqueous amine solutions. It involves capturing CO2 within a solvent (absorption) and releasing it through heat input (desorption). The needs are about 0.6 MWhth/tonnes$_{CO2}$ and 0.2 MWhe/tonnes$_{CO2}$. As the heat requirement does not exceed 100°C in theory, it is possible to use the waste heat from the XAMR® turbine to cancel the energy penalty of this process and facilitate the capture of CO2.

Decentralized and modular production of e-methanol: in addition to the advantages of the micro-generator linked to energy outputs, particularly through heats, intrinsic assets lie in its ability to be deployed in a modular manner and regardless of geography, as close as possible to the needs. The choice to develop a microgenerator makes it possible to proceed to the cooling without water and has a limited footprint. In this way, micro-generators can be deployed as close as possible to the most appropriate places, especially near CCUS installations. The power developed (80 MWth, 40 MWe) is also perfectly suited to most electrolyser and CCUS projects. In addition, the modular aspect proposed by NAAREA allows project leaders to keep up with the demand for e-methanol by adapting the industrial tool and energy supply.

6) Conclusion - The impact of NAAREA's decentralized hybrid energy systems

In conclusion, the deployment of NAAREA's XAMR® (eXtra-small Advanced Modular Reactor) represents a significant advancement in the field of decentralized and sustainable energy production, especially for non-electric applications. By combining the innovative molten salt technology with the compact and modular design of the XAMR®, NAAREA aims to construct hybrid energy systems that not only secure the local energy supply but also contribute to the broader energy transition.
NAAREA's strategic focus on non-electrical applications, such as heat production and high-temperature industrial processes, highlights the versatility and efficiency of the XAMR®. This approach aligns with the growing demand for clean, dispatchable energy solutions that can operate independently of traditional electricity grids.

The use of molten salt technology in the XAMR® provides several key advantages. It enhances safety through passive mechanisms, operates at high temperatures conducive to various industrial applications, and ensures a high degree of dispatchability and compactness. These features make the XAMR® an ideal solution for decentralized energy production, capable of being deployed close to consumption sites. This proximity minimizes energy losses and enhances the resilience and autonomy of local energy systems, thereby supporting both regular operations and emergency needs without reliance on extensive infrastructure.
The miniaturization of the XAMR® facilitates its integration into diverse settings, from district heating networks to industrial processes and critical facilities like data centers. The ability to provide both high and low-temperature heat, as well as electricity, allows for a broad range of applications, significantly expanding the potential markets for NAAREA's technology.

NAAREA's commitment to an industrial approach, including the mass production of XAMR® units within a manufacturing plant, further enhances the reliability and rapid deployment of this technology along with a limited impact on the environment on site. The business model of offering energy as a service ensures that customers receive comprehensive support, from implementation and maintenance to end-of-life management. This holistic approach not only simplifies the adoption of the XAMR® but also ensures its long-term viability and sustainability.

By providing a secure, sustainable, and adaptable energy solution, innovative microgenerators will play a crucial role in the global effort to combat climate change and achieve the goals of the energy transition.