CAPÍTULO 10

PREFEASIBILITY OF IMPLEMENTING A SMALL MODULAR REACTOR FOR ELECTRIC POWER GENERATION IN AN OIL FIELD

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ABSTRACT: A pre-feasibility study was carried out for the implementation of a small modular reactor (SMR) for continuous, clean and highly available generation of electricity for the production operations of an oil field, where half of its energy comes from fossil fuels, in order to achieve a reduction of CO2 emissions, which included:

- Identification of the regulatory and normative requirements required by the International Atomic Energy Agency (IAEA), which articulates around the world, the promotion of the use of nuclear technologies for peaceful purposes and ensuring high standards of safety and security for the implementation of an SMR in Colombia.
- Conducting a technical and economic pre-feasibility study for the use of nuclear energy for electricity generation to decarbonize the energy matrix of an oil field, replacing the use of fossil fuels to reduce CO2 emissions.
- Development of a systems integration analysis that evaluates the interaction of the SMR with the existing oil field infrastructure, ensuring technical compatibility. This analysis would include the load management to maximize the utilization of the energy generated by the SMR.

The results present the selected reactor through a comparative analysis of the progress of SMRs, using the following six conditions: licensing, siting, financing, supply chain, social commitment and fuel; incorporated in the SMR assessment used by the Nuclear Energy Agency (NEA) and the Organization for Economic

Cooperation and Development (OECD), NEA/OECD, which aim to generate confidence in the technology and identify challenges or needs of government policies in the deployment of this type of reactors.

KEYWORDS: Oil, Gas, Energy, Nuclear, Fission, Small Modular Reactor, LCOE, clean, use of land.

INTRODUCTION

Since the first industrial revolution in the mid-18th century and up to the present day, industry has made great advances and technological developments to achieve higher production volumes (Pigna, 2017). The extractive industry, both mineral and oil, has not been immune to these developments; for example, crude oil has been extracted at lower costs and several paradigms associated with the scarcity of the resource have been overcome in order to provide continuity in the global supply of fossil fuels.

SMRs, being an emerging technology, present specific challenges compared to large-scale nuclear reactors. Among these challenges are fuel cycle management and the development of effective thermal management methods at the modular level, especially in molten salt reactors (MSRs) and fast neutron reactors (FRs). Heat transfer and fission efficiency must be maximized to ensure reliable and competitive energy production relative to conventional systems. (Westinghouse Electric Company LLC, 2024). This requires the integration of advanced alloys and real-time monitoring systems for critical reactor operating parameters.

The adoption of SMR in complex industrial sectors, such as oil fields, requires a thorough understanding of the interaction between nuclear generation modules and the existing grid infrastructure. This implies not only an adaptation of electrical distribution systems, but also an implementation of advanced protocols for responding to load variations. SMRs, particularly those cooled by helium or with graphite moderators, offer exceptional thermodynamic stability, allowing efficient integration with intermittent sources. Low no-load reactivity and higher thermal limits provide additional operating margin, significantly increasing responsiveness to variations in energy demand, which reactor manufacturers such as Westinghouse indicate the reactor can operate with variations of up to 20% of the load in a minute (Westinghouse Electric Company LLC, 2024).

Reactor manufacturers, such as Nuscale, indicate that its module has the ability to vary reactor power by up to 40% per hour, which conforms to the specifications set forth by the Electric Power Research Institute (EPRI) in the document: "Advanced Light Water Reactor Utility Requirements Document, Revision 13, Tier 2, Chapter 1". To respond even more quickly to sudden changes in power demand, Nuscale's module can rapidly reduce its electrical power output by up to 10% per minute and return to full power at the same rate using turbine bypass, making it much faster than conventional nuclear reactors (NuScale Power, LLC, 2021).

OBJECTIVES

General objective

Evaluate the technical and economic pre-feasibility of implementing an SMR for electric power generation in an oil field, focusing on the ability of this system to provide continuous and low CO2 emission energy, in order to improve the availability of energy required for oil operations.

Specific Objectives

- Review of existing nuclear regulations in the country and the requirements and standards required by the IAEA.
- Record the integration of the SMR with the existing oil field infrastructure, ensuring technical compatibility and optimizing local energy availability, including the adaptation of electrical distribution systems and load management to maximize the use of the energy generated by the SMR.
- Verification of the simulations performed by the reactor manufacturer, according to the main events that may affect the power delivered by the reactor.

PROBLEM

The electricity matrix of the oil production field analyzed, whose name and location cannot be indicated due to a confidentiality agreement signed with the operating company, has half of its electricity source with fossil fuels and the other half is supplied from the grid. With this, it can be said that at least half of the energy in this matrix can be decarbonized through SMR, incorporating a more resilient energy source in the face of climate and supply challenges, using less fuel and space needed compared to other energy sources, guaranteeing, as regulated by the IAEA, control over waste from mining to final disposal. Figure 8 shows that nuclear energy sources use the least amount of space, averaging 8 ha/TWh/year (*Land-Use Intensity of Electricity Production and Tomorrow's Energy Landscape*, s. f.).

The oil production field has 350 producing wells fed through a 13.8 kV medium voltage network, which takes its energy from two sources: the first from two thermal power plants totaling 50 MW and the second through a connection to the Regional

Transmission System (RTS) at 115 kV from where another 50 MW are taken for a total of 100 MW, with the configuration shown in Figure 1. (*[Hot Item] 1MW 1MW 3MW 4MW 5MW 6MW 7MW 10MW Hfo aceite combustible pesado Hfo generador planta eléctrica con Lloyd Registrarse Lrqa de los Cssc / Man*, s. f.).

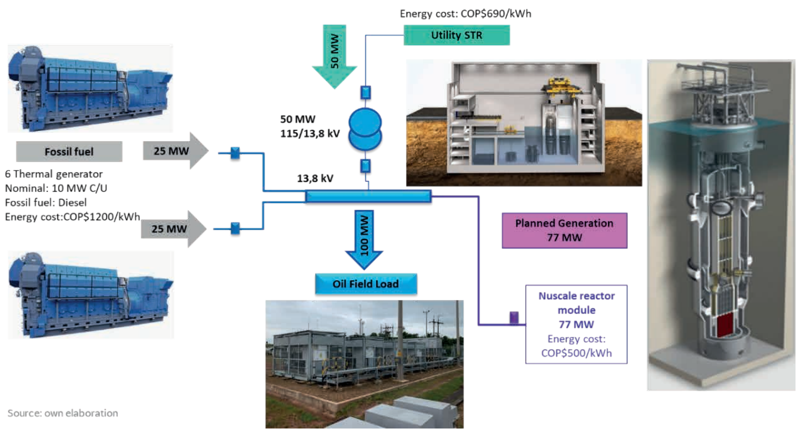

Figure 1. Schematic diagram of the power generation system in the production field. Source: own elaboration.

In order to determine the daily load curve and thus foresee demand considerations, measurements were taken with a network analyzer installed in the 13.8 kV busbar, as well as a verification of the simulations of the stability of the proposed reactor and its response to load changes. Figure 2 shows the daily load curve, which is constant and has no time slots, indicating a continuous operation 365 days a year, representing a developed and permanent industrial system.

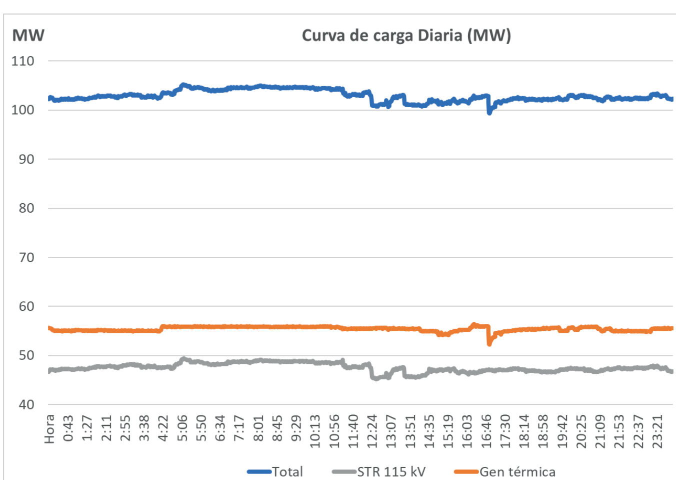

Figure 2. Daily production field load curve. Source: own elaboration.

To mitigate the environmental impact, particularly to stop the increase in global temperature as a consequence of the generation of electricity mainly with fossil fuels, which is equivalent to a quarter of global emissions, as shown in Figure 3 (Ritchie & Roser, 2024), the implementation of an SMR, defined by the International Atomic Energy Agency (IAEA) as an advanced nuclear reactor with a capacity of up to 300 MWe equivalent, pursuing economies of mass production and short construction times, is proposed.

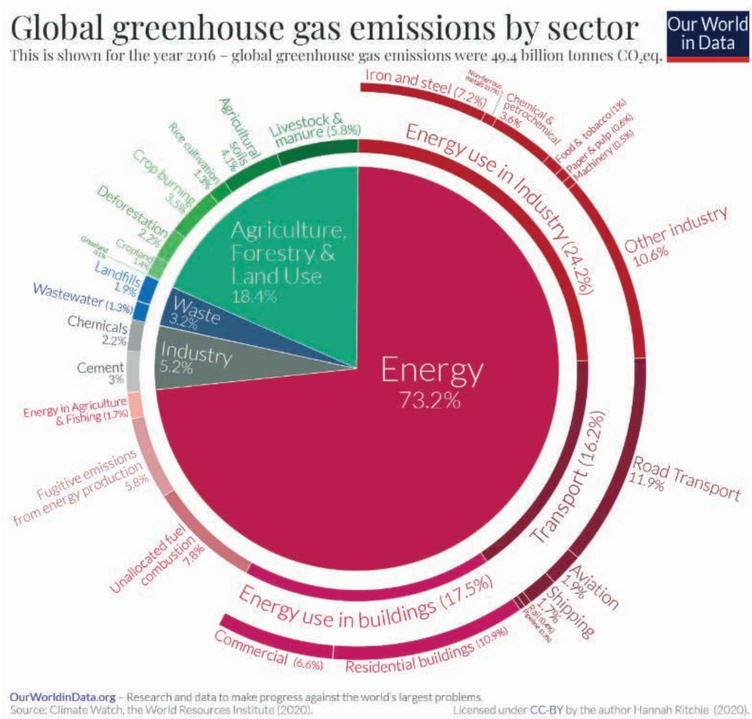

Figure 3. Global greenhouse gas emissions by sector.

STATE OF THE ART

The focus will be on Generation III+ (some under construction) and Generation IV reactors, since these are the designs that will have the greatest deployment in the next decade and have incorporated the lessons learned from sixty years of operation of nuclear reactors of previous generations, which has allowed improving their modularity, cost structure and safety aspects.

Generation I, operated between the 1950s and 1960s, were mainly prototypes. Generation II started in the 1970s and corresponds to most of the reactors currently in operation. Generation III was designed in the nineties, incorporating advances in safety and costs, mainly in Asia. Generation III+ is an improvement in terms of construction methods and incorporation of safety elements, several are currently under construction and are expected to start operation around 2030. Generation IV reactors adjusted their modularity, improved safety features, optimization in fuel use and more severe conditions to avoid their use in weapons proliferation as summarized in Figure 4 (H. Khalil et al., s. f.).

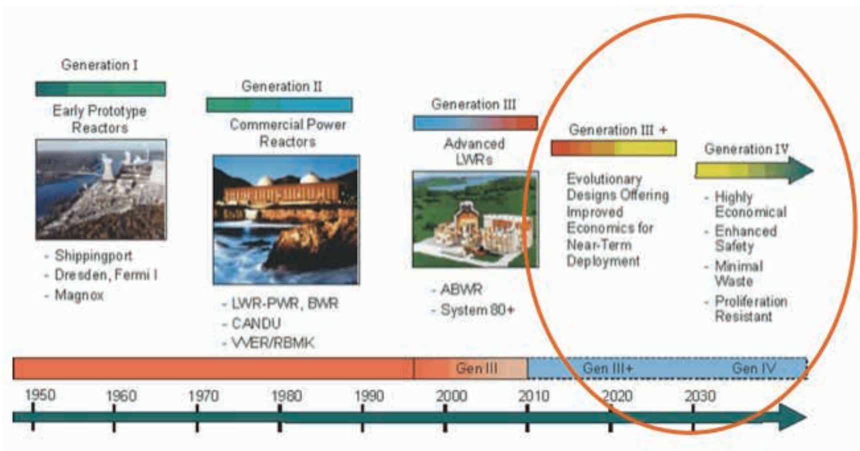

Figure 4. Nuclear reactor generations (H. Khalil et al., s. f.).

STATE OF THE ART IN NUCLEAR REACTOR OPERATIONS

According to (International Atomic Energy Agency, 2024), As of June 2024, there were 418 reactors operating in 31 countries with an installed capacity of 371.5 GWe, which, as shown in Figure 1, has an approximate share of 10% of the world's energy mix.

Globally, there are 59 nuclear reactors under construction in 17 countries with a capacity of 61 GWe, led by China with 24 reactors and an estimated 25 GWe, followed by India with 4 reactors totaling 6 GWe and Turkey with 4 reactors and a capacity of 4.4 GWe, only these three countries are installing 58% of the capacity to be incorporated in the next five to ten years.

La Agencia Internacional de Energía, en su reporte el camino para una nueva era de la energía nuclear, prevé mas de mil (1000) SMR en operación para 2050, adicionando una capacidad instalada de 120 GWe principalmente en China, Estados Unidos, La Unión Europea, India y el Reino Unido como se ve en la figura 27 (*The Path to a New Era for Nuclear Energy – Analysis*, 2025). La incorporación de SMR están tomando relevancia dada su modularidad, menores tiempos de construcción, apoyo de los gobiernos, menores costos y nuevos modelos de negocios, que permitirán tener una energía gestionable, continua y limpia, impulsada también por el incremento de la demanda del sector privado (*The Path to a New Era for Nuclear Energy – Analysis*, 2025).

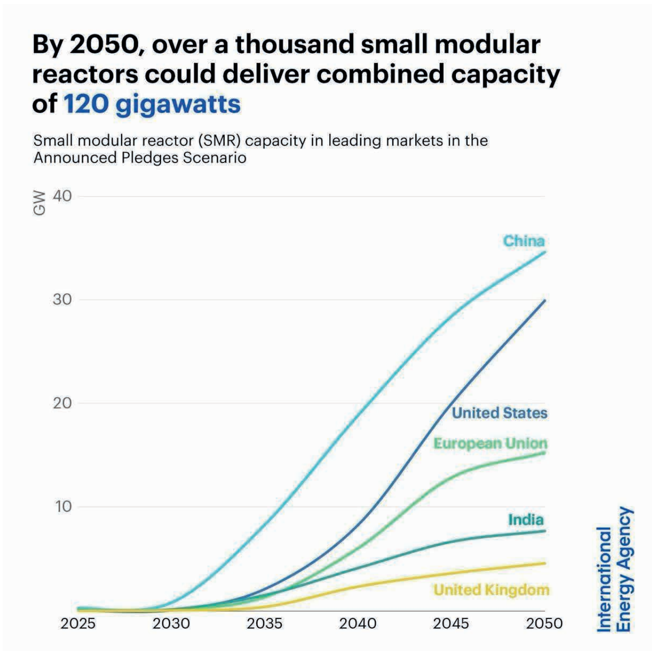

Figure 5. Projected IEA deployment of nuclear reactors to 2050 (H. Khalil et al., s. f.).

STATE OF THE ART IN COSTS

In the table 1 (Torres Diaz & Ronningen, 2024) lists the investment costs per MW (CAPEX) of plants that have come on line from 2023 to those that will come on line by the end of 2025, this Global Nuclear Energy Review 2024 report by RystadEnergy (Torres Diaz & Ronningen, 2024), shows a large difference in costs in favor of the Generation III+ reactors with three Generation III designs, which have had a series of atypical situations described below that have greatly increased their costs and construction times and have served as lessons learned for the new Generation III+ and IV reactor designs.

Economics of selected large-scale plants recently commissioned or under development Rystad

Plant	Location	Capacity (MW)	Planned start-up	Cost (USD billion)	Capex (USD million per MW)
Hinkley Point C	UK	3,260	Jan-31	44	13.5
Flamanville 3	France	1,650	Jun-24	20.6	12.5
Shidaowan 1	China	1,500	Jun-25	7.9	5.3
Barakah 3	UAE	1,400	Feb-23	6.1	4.4
Shin Hanul 1	South Korea	1,340	Dec-22	6	4.5
Shin Kori 5	South Korea	1,340	Dec-24	4.4	3.3
Kursk II-1	Russia	1,255	Dec-25	3.8	3.0
Vogtle 4	US	1,250	May-24	15	12.0

Table 1. CAPEX costs per MW of plants entering operation.

RESULTS

o reliably assess the progress of SMRs, the following six conditions incorporated in the NEA/OECD assessment were used to build confidence in the technology and identify challenges or government policy needs in the deployment of this type of reactor; in turn, it provides the most comprehensive assessment to date of progress towards commercialization of SMRs, identifying those designs that are making significant progress towards commercial deployment and those that are in earlier stages of development (*The NEA Small Modular Reactor Dashboard*, s. f.).

A comparison of the six conditions in the models with the highest level of technological maturity TRL (Technology readiness level) was made, as shown in Figure 6. (*The NEA Small Modular Reactor Dashboard*, s. f.).

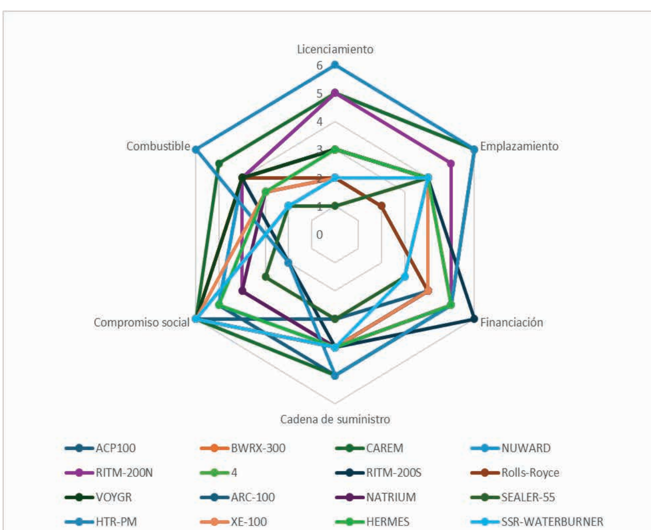

Figure 6. Comparison of reactors with higher technological maturity.

Source: Own elaboration with information from NEA/OECD.

For the 77 MWe module, which is expected to operate with a capacity of more than 50 MWe, a total investment of ThUS$308.47 was estimated over ten years, as shown in Figure 7, including pre-construction, detailed engineering, construction, management, contingencies, start-up, facility construction costs and financial costs, among others.

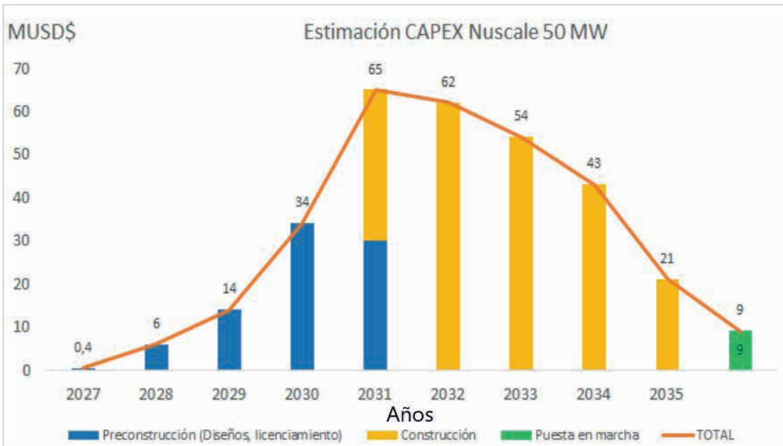

Figura 7. Estimated SMR investment 77 MWe. Source: own elaboration.

A comparison of variables associated to generation with fossil fuel (diesel) and generation with SMR, shown in Table 2, shows that there is a negative economic valuation for those technologies high in CO2 emissions and its economic model is punished with USD$30/Ton CO2, this scheme encourages the use of low emission technologies in new projects and in the case of SMR gives a bonus of MUSD$6.6. There is also a savings of ThUS$38/year due to the difference in energy tariffs and a business option of being able to commercialize the diesel and oil used for energy generation for a sales value of ThUS$18/year; adding these benefits together, annual savings of ThUS$62.65 are achieved with a return on investment period of five years.

The levelized cost of energy (LCOE) model of SMRs presents a clear competitive advantage over conventional diesel systems, particularly when considering the social and environmental costs associated with carbon emissions. This analysis, which integrates reactor construction, maintenance and disposal costs, reveals economic superiority in continuous high demand scenarios. SMRs, by operating on extended maintenance cycles and low fuel turnover, optimize operating costs and ensure a stable and scalable energy supply without dependence on seasonal factors. In addition, savings in negative externalities, such as CO2 and SOx emissions, translate into direct benefits for the region by reducing the need for environmental offsets and improving public health indicators

Variable Assessed	First Year Diesel	First Year SMR
Energy to be replaced (MWh)/year	438.000	674.520
Estimated (TON CO2e)/year	220.752	26.490
Shadow price reduction (MUSD)	0	$6,62
Levelized cost of energy LCOE (USD/MWh)	210	80
Nominal Generation Capacity (MWe)	50	77
Nominal Plant Factor	0,86	0,92
Actual Energy Generated (MWh)	376.680	620.558
Cost of Energy Generated (MUSD)	$91,98	$53,96
Crude Oil Consumption (BOPD)	534.725	0
FO#4 Consumption (BPD)	49.275	0
Margin of crude sale (MUSD/BLS) @30 USD/BL	0	$16,04
Selling FO#4 margin (MUSD/BLS) @40 USD/BL		$1,97
Initial SMR Investment (MUSD/MW)		$308,00
Annual Profit (MUSD)		$62,65
Payback time (years)		4,92

Tabla 2. Economic comparison Diesel and SMR. Own elaboration with information from the field and Nuscale.

CONCLUSIONS AND/OR FINAL CONSIDERATIONS

It is possible to diversify the energy used in the oil production field and replace fossil fuel sources with nuclear energy through SMRs, which provide continuous, low-emission energy without price variability due to climatic phenomena such as El Niño. This would make it possible to configure a diversified and resilient electricity matrix in the face of climate and fossil fuel supply challenges.

The analysis shows annual benefits of ThUS$62.6 million, which leverages the investment and allows recovering it in less than 5 years, confirming what was seen in the theoretical framework. The financial model will need to be adjusted as the results of the start-up of the SMRs that have already begun construction unfold.

A fast response time of the safe shutdown of the reactor to the events and disturbances presented in the simulations is observed, which indicates that the control system is robust and provides a safe response to the contingencies evaluated.

The government - business - academia articulation is important, as efforts will be required to formalize careers associated with nuclear technologies. It is recommended to make alliances with countries with significant progress in this area (Argentina, United States, France, Russia, Korea, China, among others), establishing in turn the generation of higher quality and better paid jobs.

There are 32 countries in the world that use nuclear energy and plan to continue using it to generate electricity, in addition to 10 countries that plan to build SMRs. A resurgence of nuclear energy is clearly observed, with a cut-off date of July 2024.

SMR designs use less fuel because they increase the frequency of energy replenishment, thus improving operating costs, have less waste and boast the lowest land use compared to other energy sources.

The results of the effort made by the Ministry of Mines and Energy are observed, regarding the updating of the regulations associated with nuclear technologies, for example: Resolution 40234 of July 4, 2024: "Whereby the requirements for physical security in the use of category 1, 2 and 3 radioactive sources are established...", and Resolution 40306 of August 5, 2024, 'Whereby the regulations for the safe transport of radioactive materials are updated', showing a clear commitment by the Ministry of Mines and Energy to update its regulations on nuclear matters, aligning the national regulation with the IAEA guidelines and directives.

It is advisable to continue with technology watch to develop the feasibility study and the studies associated with the milestone approach suggested by the IAEA for the deployment of a nuclear program.

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