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ANALYSIS OF DESIGN FEATURES OF PROMISING SMALL POWER REACTORS

Abstract: In Bolivia, nearly 70 % of electricity generation is based on fossil fuels, and the main source is gas, the production of which is decreasing considerably in the country. The need to diversify Bolivia's energy sources is stressed to secure a stable supply and lower carbon emissions. With significant advancements in nuclear technology, facilitated mainly by Rosatom Corporation over the past nine years, this country has established a foundation for nuclear energy development by installing three critical nuclear components: a multipurpose irradiation plant, a research reactor, and a cyclotron. As these facilities near completion, it should now transition to the next phase: integrating nuclear power into its energy portfolio, considering that the implementation of nuclear power is long term and requires the prior development of its infrastructure. Under these conditions, this research work evaluates various sources of energy based on traditional feasibility metrics, addressing key concerns such as safety and public acceptance, energy demand, infrastructure, economic viability, environmental impact, most of them oriented by the International Atomic Energy

Agency (IAEA) in order to generate parameters for analyzing and then identifying a proper source that aligns with Bolivia's energy needs and development objectives. Finally, this study aims to provide recommendations for selecting a suitable nuclear power reactor that would be used by other developing countries as a starting point when evaluating the incorporation of nuclear power.

Keywords: facility, energy source, power reactor, carbon emissions, development.

Introduction

First, according to the latest data published by the International Energy Agency (IEA) [1], in Bolivia, the main source of electricity generation in 2022 was natural gas with more than 60 %, followed by hydroelectric with 25 %. Likewise, these data indicate that there was an increase in electricity generation with natural gas sources from 2,278 GWh in 2004 to 7,005 GWh in 2022; while the hydroelectric evolution went from 2,149 GWh to 2,851 GWh in the same period. A significant increase in electricity generation was unleashed. However, according to 2025 data from the International Monetary Fund (IMF) [2], since 2014, revenues from natural gas exports have decreased by 70 %, and one of the main reasons is the decrease in domestic production due to insufficient investments; what is more, fuel imports increased from 4 % to 9 % of GDP. Consequently, Bolivia needs to incorporate new sources into its energy matrix or increase the ones it already has.

Second, according to Emissions Database for Global Atmospheric Research (EDGAR) [3], in 2023 global Green House Emissions (GHE) reached 53.0 Gt CO_{2eq}, the majority of GHG consisted of fossil CO_2 accounting for 73.7 % of total emissions, while CH_4 contributed for 18.9 % to the total, N_2O for 4.7 % and F-gases for 2.7 %. Global fossil CO_2 emissions increased by 72.1 % since 1990. In the case of Bolivia, it has increased since 1990 by 86 %; from 29,621 to 55,186 Mt CO_{2eq} in the same period. An important fact is that if we focus on the GHE per capita, the increase is low, from 4,320 t CO_{2eq} to 4,585. Therefore, the increase is essentially due to the increase in population, which almost doubles the figure. However, Bolivia's governmental strategic documents [4] show a policy of transition to renewable energies. This is the other argument for Bolivia to consider changing the energy matrix to other renewable and clean sources.

Third, over the last nine years, Bolivia has implemented a new Nuclear Program [5] with the support of the IAEA and has chosen Rosatom Corporation as its main partner. As a result, there is an important progress of a Nuclear Research Center that houses three main components, among them a nuclear research reactor that could start operating in 2025 and that will have the main function of training and education due to its characteristics.

In this context, the South American country meets the appropriate conditions to enter an energy transition that can be used to accelerate the technology transfer through a nuclear power reactor considering the typology according to the needs and current scientific-technological advances, which can not only be used for nuclear development but also to revolutionize science, technology and local industry, as it is suggested by IAEA [6].

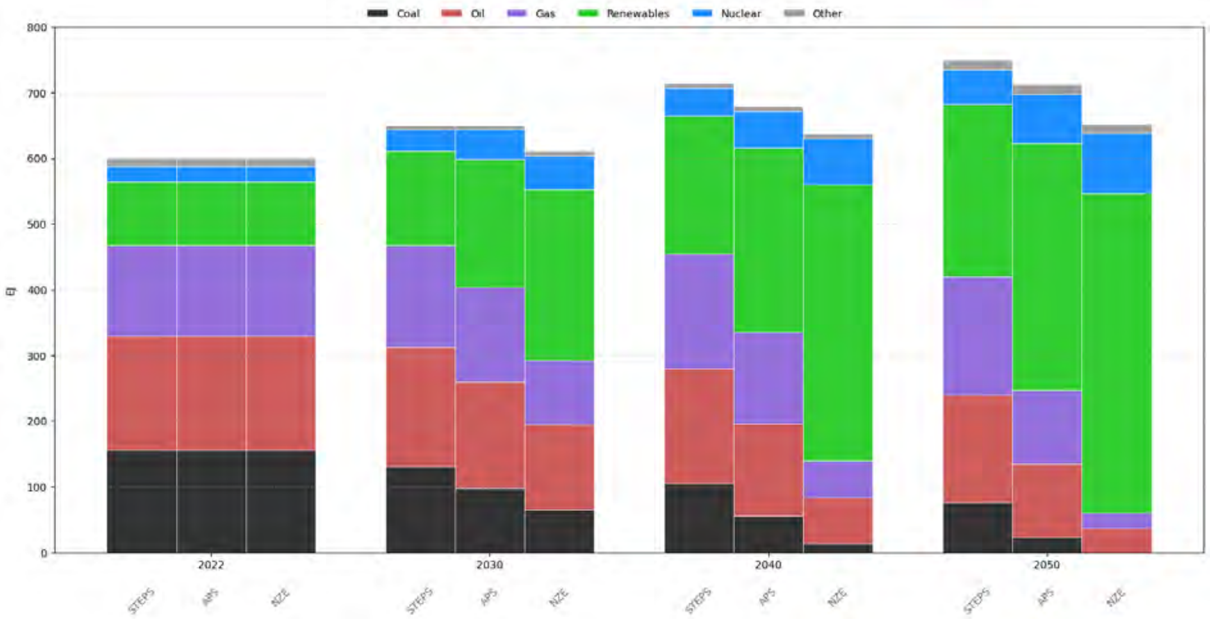
Background and Perspectives

World's energy

According to IEA [7], currently, energy demand is constantly increasing at an average of 1.4 % per year, unlike electricity demand, which is growing at an accelerated rate of 2.7 %. While the energy transition towards zero emissions depends on the assumed policies.

Energy demand in the period from 2013 to 2023 has increased by 15 %, and of this percentage, 40 % corresponds to clean energy, which includes renewables in power and end-use sectors, nuclear, low-emissions fuels, and so forth. With this rapid development of clean energy, there are favorable prospects for renewables, nuclear, and low-emission fuels, including carbon capture, utilization and storage.

In all the scenarios proposed by the IEA to 2050, according to Fig. 1, clean energies show accelerated growth. These scenarios are STEPS (Stated Policies Scenario), APS (Announced Pledges Scenario), and NZE (Net Zero Emissions).



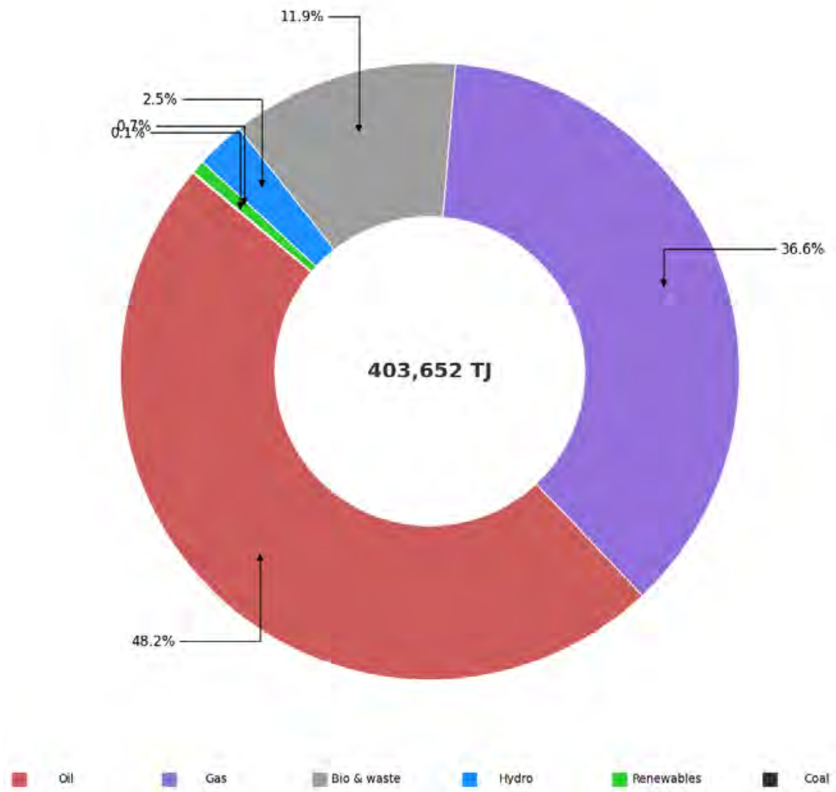
Source: compiled by the author

Fig. 1. Global energy mix by scenario to 2050

It is important to highlight that for the scenario close to 2030, clean energies could have a share of up to 50 % of all energy consumed. This is favorable for the nuclear industry and the energy development plans of each country.

Bolivia's energy development

In the last ten years, Bolivia has increased energy consumption from 312,768 TJ in 2003 to 403,652 TJ in 2022. Of the total energy consumption, more than 82 % corresponds to gas and oil derivatives.

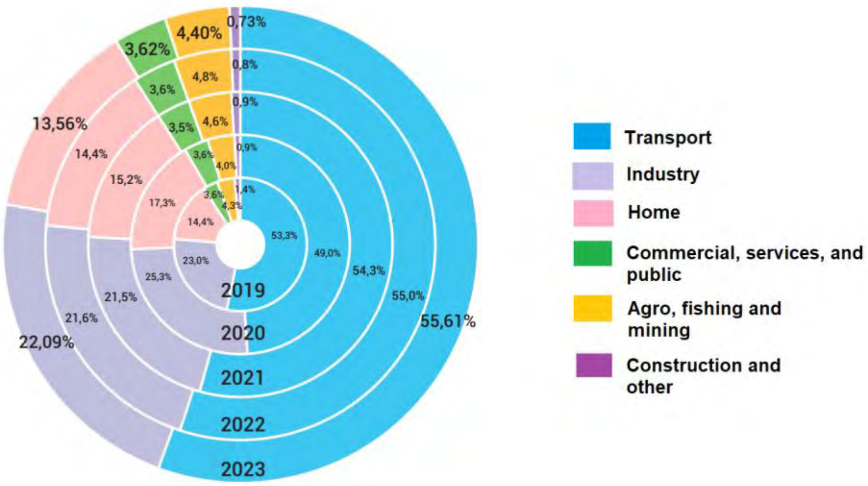


Source: compiled by the author

Fig. 2. Total Energy Supply 2022

An issue that makes it difficult to continue with the same energy matrix is the uncertainty of gas sources, which in recent years have experienced a deterioration in production and exports; likewise, both gasoline and diesel, which are subsidized by the State, have suffered a shortage in the face of growing demand, taking into account that Bolivia does not have a significant production that can meet domestic demand, so it has to import it. Likewise, more than 50 % of the total energy demand is consumed by the transportation sector, followed by the industrial and residential sectors [8].

In this context, Bolivia is under pressure to change its energy matrix and avoid a crisis that could affect all sectors, taking into account that the current matrix is mainly based on fossil fuels.



Source: extracted from reference [8]

Fig. 3. Energy Consumption by Sector

Bolivia's nuclear development

Starting in 2015, Bolivia renewed a peaceful nuclear program through the creation of the Bolivian Nuclear Program (PNB) and later in 2016 the Bolivian Nuclear Energy Agency (ABEN). Organizationally, the PNB represents the Government, the ABEN the Nuclear Energy Programme Implementing Organization, an electricity and nuclear technology authority the Regulatory Body, and again the ABEN the Owner Operator; all these organizations within the organizational chart of the Ministry of Hydrocarbons and Energies, i.e. belonging to the State.

Based on the IAEA Milestone Approach for research reactors [9], Bolivia would have complied with the three phases according to the milestones for the nuclear facilities it incorporates, highlighting a research reactor; however, it would require the development of a special nuclear infrastructure for a nuclear power plant, since it still does not have a national position on the nuclear option as a source of electricity.

The nuclear facilities are:

- Three nuclear medicine and radiotherapy centers.
- Preclinical radiopharmacy cyclotron complex.
- Multipurpose irradiation center.
- Research reactor.
- Radiobiology and radioecology laboratory.

Nuclear facilities correspond mainly to Rosatom Corporation's integrated approach called Rosatom Center for Nuclear Science and Technology [10]. The Russian corporation has supported the construction of more than 120 research reactors; 20 projects based on this proposal have been implemented outside Russia, making up approximately 20 % of existing research reactors worldwide.

For analytical purposes, we will take as a reference the nuclear research reactor called BRR-1, which is likely to start operation in 2025.

Table 1

Some technical characteristics of the BRR-1

Feature	Description
Name:	BRR-1
Maximum design heat capacity	200kW
Cooland	H2O
Temperaure	35 – 44 °C
Reflector	Berilium
Assemblies in the reactor core	72, VVR-M2
Reactor life time	>50 years
Fuel enrichment U-235	19.7 %
Type	Pool Water
Status	Under construction

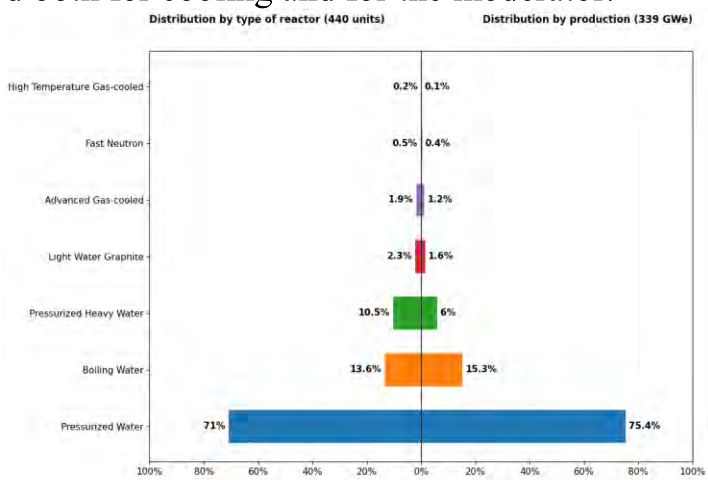
Compiled by the author

This data will be useful for the relationship with Small Modular Reactor (SMR) technologies and designs to consider them with greater technological compatibility, but it will also allow us to take into account the development of the nuclear infrastructure achieved thanks to the incorporation of nuclear facilities in progress.

NUCLEAR POWER REACTORS

Nuclear Power Reactors

In 2022, nuclear reactors have generated approximately 2,667 TWh worldwide, where the main production regions are Europe and North America; however, there has been a sustained growth in Asia in the last ten years [11]. As for the types of reactors that are most widely used, pressurized water reactors should be highlighted. Likewise, water is used both for cooling and for the moderator.



Compiled by the author

Fig. 4. Types of nuclear power reactors in the world and their capacity in percentage

An important data to be collected is the evolution of nuclear power generation in recent years and the immediate prospects that allow us to know a significant increase. In the last fifty years the increase in the use of nuclear energy, despite a reduction between 2010 and 2012 due to the Fukushima Daiichi accident in Japan, has increased from 111 TWh in 1971 to 2,667 TWh in 2022; moreover, the outlook for increase by 2026 is 2,958 TWh. These data confirm that nuclear power will continue with the growth pattern according to Fig.1.

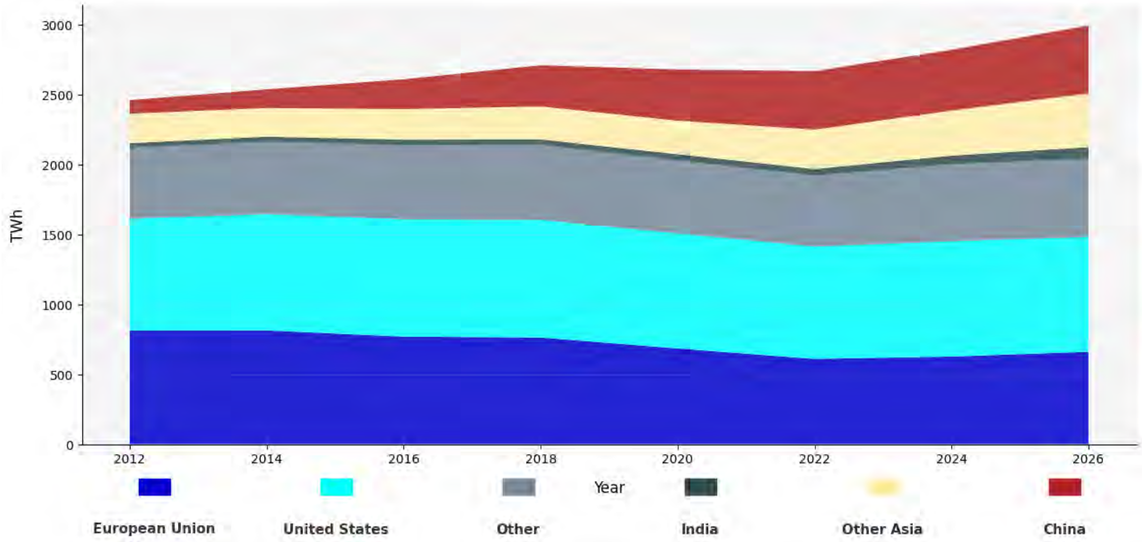


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Fig. 5. Evolution of nuclear power generation by region, 2012–2026

Another important fact concerning nuclear reactors that are planned for energy supply in the face of demand is generation. That is, the increase in the use of nuclear energy is accompanied by scientific and technological advances in the nuclear industry that allow especially two things: the multi-objective optimization of problems for the reduction of both cost and pollution.

According to the literature consulted on some scenarios proposed according to reactor generation [12], it is established that costs can be reduced by 3 % with the use of Generation III+; and with Generation IV by 11 %; likewise, the use of Generation IV with the generation of a new combined cycle by 28 %.

Finally, a relevant aspect of nuclear reactors is the power related to the energy demand that also allows the country receiving this technology to adapt and develop its scientific capabilities with advantages proportional to the development achieved; these are the SMRs.

Small Modular Reactors

In 2023, at the United Nations Climate Change Conference, nuclear technology was included to be implemented to achieve zero carbon emissions. SMRs have many advantages not only because of their adaptability in less well-developed contexts but also because of their low carbon emissions. Because they are modular, they can be implemented in remote areas where energy demand is not very high, as transmission costs through electrical grids are usually very high.

Currently, according to IAEA data from the Advanced Reactor Information System Database (ARIS) [13], there are about seventy SMRs designs worldwide, with a capacity of about 300 MW(e) per unit with a design of advanced safety features, which also incorporates the best available technology from other conventional and experimental reactors, including the main ones shown in Fig. 4; thus, this type of reactor enjoys global interest, promoted by powers such as Russia and China.

A fundamental aspect to refer to the different SMRs is their capacity to be introduced in embarking countries that are in the initial stage of their scientific and technological nuclear development, as is the case of Bolivia.

In this sense, it is essential to characterize the different SMRs, based on data collected selectively and systematically by the IAEA [14, 15], a document that recognizes the potential of these reactors as a viable solution for energy security for developed or developing countries. Likewise, this organization provides technical support to interested countries to develop their nuclear infrastructure, a topic that will be addressed in the following section.

For illustrative and practical purposes, following the IAEA categorization of SMRs, only those designs with demonstrated sustained development will be taken into account, taking into account that there are more than one hundred designs worldwide; however, for analytical purposes, we will take into account those that reached the following statuses: detailed design, operational, under construction, and in operation.

Table 2

Design and main features of SMRs around the world

Design/Type reactors	Name	Output MW (e)	Service life (years)(years)	Refueling (months)	Fuel enrichment %	Safety System	Gen.	Country/Company	Status
Water Cooled	ACP100	125	60	24	<4.95	Passive	III	China / CNNC	Under construction
	BWR X-300	300	60	12-24	<4.95	Defense-in-depth, passive	III+	USA and Japan / Westinghouse Electric Company, LLC	Detailed design
	CAREM	30	40	14	3.1	Passive	III	Argentina / CNEA	Under construction

	Happy200	200	60	18	<4.45	Active / passive	III+	China / SPIC	Detailed design
	NuScale Power Module	77	60	18	<4.95	Passive	III+	USA / NuScale Power Inc.	Detailed design
	PWR-20	20	42	72	<4.95	Defense-in-depth, passive, redundancy	III+	USA / Last Energy	Detailed design
	RITM-200N	55	60	60-72	<20	Active, passive	III+	Russia / JSC Afrikanov OKBM	Detailed design
	SMART	107	60	30	<5	Passive	III+	Korea and Saudi Arabia / KAERI and K.A. CARE	Detailed design
	Rolls-Royce SMR	470	60	18	<4.95	Active, passive	III+	UK / Rolls-Royce	Detailed design
Water Cooled (Marine based)	ABV-6E	9	40	120-144	<20	Passive	III	Russia / JSC Afrikantov OKBM	Detailed design
	KLT-40S	2x35	40	30-36	18.6	Active (partially passive)	II+	Russia / JSC Afrikantov OKBM	In operation
	RITM-200M	50	60	120	<20	Active, passive	III+	Russia / JSC Afrikantov OKBM	Detailed design
	VBER-300	325	60	72	4.95	Hybrid (passive and active)	III+	Russia / JSC Afrikantov OKBM	Detailed design
High Temperature Gas	HTR-10	2.5	20	On-line	17	Active, passive	IV	China / INET, Tsinghua University	Operational

Cooled	HTR-PM	210	40	On-line	8.5	Active, passive	IV	China / INET, Tsinghua University	In operation
	HTTR	30	~20	~20	6	Active	IV	Japan / JAEA	In operation
Fast Neutron Spectrum	4S	10	60	N/A	<20	Hybrid (passive and active)	IV	Japan / Toshiba Corporation	Detailed design
	BREST-OD-300	300	30	36-78	<14.5	Passive	IV	Russia / NIKIET	Under construction
	SVBR-100	100	50	72-84	<19.5	Passive, integral layout	IV	Russia / JSC AKME Engineering	Detailed design
Molten Salt	CA Waste Burner	N/A	5-50	N/A	N/A	Passive	IV	Denmark / Copenhagen Atomics	Detailed design
	IMSR 400	195	56	84	<5	Passive	IV	USA, Canada / Terrestrial Energy Inc.	Detailed design
	KP-FHR	140	20	On-line	19.75	Passive	IV	USA / KAIROS Power, LLC.	Under construction
Microreactors	HOLOS-QUAD	10	40-60	96	19.95	Passive	IV	USA / HolosGen	Detailed design
	HOLOS-MONO	10	40-60	96	19.95	Passive	IV	USA / HolosGen	Detailed design
	Jimmy	10	10-20	No	<19.75	Passive	IV	France / Jimmy Energy SAS	Detailed design

Compiled by the author

Assessment

In order to evaluate the different types, designs and technologies of SMRs, this research work takes as a methodological reference four analytical elements that will lead to a model of a nuclear power reactor that could be incorporated in Bolivia with the purpose of taking advantage of the ongoing nuclear involvement and the need to diversify the local energy matrix; critical conditions that may allow this country to develop in the nuclear industry.

Multi-criteria analysis to select an energy source

Decision making represents challenges that require a comprehensive and constantly improving approach to decision making. Multi-criteria decision analysis (MCDA) is a model that combines quantitative and qualitative elements with objective multiples and criteria that has grown out of research related to the development of computational and mathematical tools to support subjective evaluations and criteria development [16].

According to this model applied to energy, it takes into account economic, environmental, social and other aspects. One of the difficulties in applying this method is the selection of appropriate criteria. The other difficulty is to use the qualitative criteria to convert them into numerical data that can be measured against each other, taking into account that a full comparison is difficult.

According to a study applied to renewable energies, including nuclear energy [17], using three stages for its analytical development, on the one hand; the establishment of comparative criteria and the designation of values to these criteria, where experts related to the area were involved for their establishment. On the other hand, the normalization of indicators by means of the following equations:

For discounted profit, power generation, efficiency, etc.:

$$k_i = \frac{C \cdot x_i}{1 + C \cdot x_i} \tag{1}$$

with

k_i = a normalized criterion,

C = a normalized factor,

x_i = an initial absolute value of the criterion.

When x_i is in the range $0 < x_i < \infty$, the value of the normalized criterion changes from 0 to 1.

For a criterion that decreases with increasing value, the inverse equation is used:

$$k_i = \frac{1}{1 + C \cdot x_i} \tag{2}$$

The value of the normalized criterion changes from 1 to 0. This formula can be used for discounted costs, the cost of energy production, material resource consumption, period, etc. If the values are negative, the formulae for increasing or decreasing criteria will take the following form:

$$k_i = \frac{a^{x_i}}{a^{x_i} + 1} \tag{3}$$

$$k_i = \frac{1}{a^{x_i} + 1} \quad (4)$$

where α is base of degree greater than one.

For qualitative criteria, the research suggests: «very bad» – 0.1, «bad» – 0.3, «satisfactory» – 0.5, «good» – 0.7, and «very good» – 0.9. While 0 and 1 are considered exceptional cases.

Table 3

Criteria and values

<table>
<tr><th>Criteria groups</th><th>Values</th><th>Final result</th></tr>
<tr><td>Economical</td><td>31.0 %</td><td rowspan="7">Closed nuclear fuel cycle can compete with renewable sources such as wind and solar power plants. However, due to constant and unpredictable development the ratio criteria may also change over time</td></tr>
<tr><td>Technical specifications</td><td>10.0 %</td></tr>
<tr><td>Sustainable energy development</td><td>8.2 %</td></tr>
<tr><td>Promising energy development</td><td>10.6 %</td></tr>
<tr><td>Safety and reliability</td><td>21.6 %</td></tr>
<tr><td>Technology maturity</td><td>7.4 %</td></tr>
<tr><td>Environmental</td><td>7.0 %</td></tr>
</table>

Compiled by the author according to the reference [17]

Special considerations

In addition, there are particular factors that merit attention, according to the previous information reviewed related to Bolivia's development, which can be summarized as follows:

Table 4

Special considerations for Bolivia

	Continuous development	Technology Transfer	Partner Country
Reasoning:	Opportunity to take advantage of power technology.	Opportunity to involve local industry and universities to develop not only nuclear technology but other industrial areas.	Russia has supported technically nuclear development in Bolivia with its integrated proposal.

Compiled by the author

Multi-criteria decision model to select a nuclear power reactor

A holistic approach in taken that involves three categories: economic, operational, and risk concerns [18]. Under this approach, decision making is a complex process involving a significant number of stakeholders and decision criteria. According to this model, SMR and Molten Salt Reactor designs are described as being on par with Pressurized Water Reactors, the latter being preferred for decades, as demonstrated in

Fig.4. It is important to point out that the results of the selection of nuclear-electric reactors correspond to the United States, a country with more than one hundred nuclear reactors, a contrast that will be important when taking into account that developing countries do not have such experience or scientific-technological progress.

Table 5

MCDA applied to nuclear power reactors

Model Applied	Comparison	Results	Directions
Analytic Hierarchy Process	Experts provided priorities and criteria selection	Preferred reactors: Traditional SMR	Encouragement to expand decision-making studies to reach a more holistic approach.

Compiled by the author

Nuclear Infrastructure (NI)

The NI for both research reactors and power reactors are similar and can be developed simultaneously, taking advantage of the benefits of incorporating nuclear facilities. The IAEA has generated a NI model based on three milestones with three phases that are interdependent, starting with the incorporation of the nuclear option in the national energy strategy and ending with commissioning and decommissioning. In order to achieve the milestones, 19 issues must be considered [19], and 20 issues according to Rosatom plan [20].

The following Table 6, will provide preliminary information on the development of milestones according to the available sources consulted, taking into account that Bolivia started the first activities related to the incorporation of nuclear facilities through its nuclear program as of 2015, assuming that the phases to develop a NI take between 10 and 15 years. This preliminary assessment will serve to consider the type of nuclear power technology to be incorporated, as a second stage of nuclear development in Bolivia.

Table 6

NI issues development in Bolivia

Undeveloped	In process	Developed
• National position • Funding and financing • Management • Electrical grid • Site and supporting facilities • Nuclear fuel cycle • Radioactive waste management • Industrial involvement • Procurement	• Nuclear safety • Safeguards • Regulatory framework • Legal framework • Radiation protection • Human resources • Stakeholder involvement • Environmental protection • Emergency planning • Nuclear security	• Some of the issues presented were almost developed focused on non-energy applications such as: • National position • Site and supporting facilities • Human resources

Compiled by the author

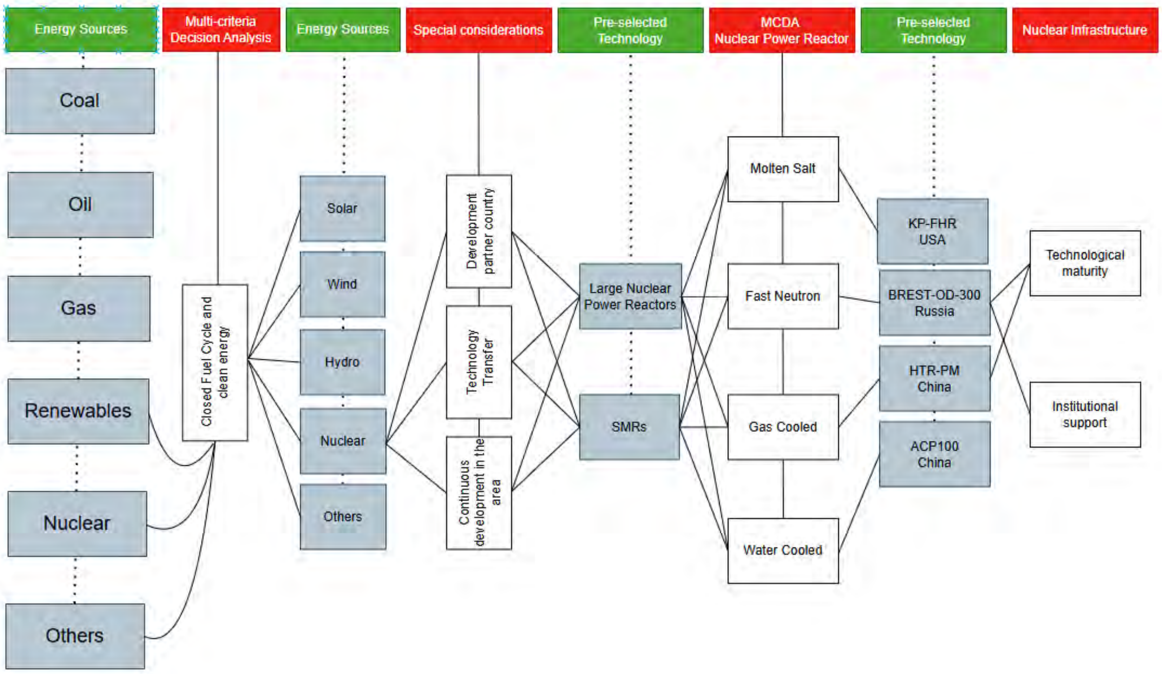
The criticality of the Nuclear Research Center could correspond to its financing once it starts operating. Another critical element is its administration, since nuclear institutions have not been institutionalized and do not incorporate the university or industry in their development and operation.

On the other hand, it should be noted that the procedures and requirements for the development of the NI for a power reactor are much stricter, so a special NI will be required. With these data, it can be considered that the incorporation of an experimental reactor or one under development could not be an option, but one that has a mature technology and design, in addition to previous institutional support.

Results and Discussion

Based on the analysis of energy sources and their relationship with the demand that suggests a change in Bolivia's energy matrix, it is appropriate to develop a preliminary modeling of the appropriate energy source to meet the growing energy demand.

In this context, with the systematized information and results obtained in the previous sections, the most appropriate sources and technologies for the case of Bolivia will be modeled.



Compiled by the author

Fig. 6. Energy source and reactor design analysis for Bolivia

There are different methods to evaluate SMRs technologies, however, the parameters used according to multi-criteria may be the most appropriate, taking into account that it takes more than a decade to develop the nuclear infrastructure.

By means of the tools used and information processed by previous studies, qualitatively, the relationship between energy sources without greenhouse effect emissions and general aspects as described were taken into account in the first instance. Secondly, particular aspects in the Bolivian context were taken into account. In third instance, the multi-criteria decision model applied to nuclear energy is taken into account and finally the development of the nuclear infrastructure in Bolivia that suggests incorporating mature technologies and the experience of institutional support. It should be clarified that the four SMRs options mentioned are pre-selected.

Conclusion

It is concluded that applying the tools considered in this research work, nuclear energy has relevance among the other sources due to its contribution to the environment, a closed fuel cycle, opportunities for scientific, technological and industrial development, adaptability in contexts not very well developed in the case of SMRs, competitiveness with other renewable energy sources such as solar and hydro; with the advantage that nuclear energy is a technology in full development that has already reached levels that have allowed advanced countries to build Gen III, III+ and IV reactors. Of which, due to the development of the Bolivian Nuclear Infrastructure, the suggestion according to the type of reactor (PWR) would be a reactor similar to the Chinese ACP100; however, due to the maturity of the implemented technology, both the Russian BREST-OD-300 reactor and the Chinese HTR-PM are the favorites, although Russia has the great advantage due to its institutional support. In summary, fast neutron reactors are the best option according to this report, although it is evident to deepen and incorporate new parameters to obtain a more justified modeling.

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EXAM ANXIETY ACROSS ASSESSMENT FORMATS: A GAUSSIAN ANALYSIS

Introduction

Anxiety is a multifaceted emotional response that encompasses feelings of apprehension, worry, and tension usually triggered by either anticipated or ongoing stressors. This normal human experience can escalate into disorders when it interferes significantly with daily functioning and quality of life. Among various forms of anxiety, examination anxiety, specifically, has emerged as a significant concern in educational settings, affecting university students across different academic levels. This specialized form of anxiety, characterized by intense nervousness before, during, and after exam periods, can adversely impact students' performance and overall mental