Methodology for Generation IV Reactor Technology selection with sensitivity analysis for future Nuclear Power Expansion Programmes

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Abstract

Electricity production around the world has been increasing rapidly with population growth. Different sources like coal, wind, solar, hydro, geothermal and nuclear are part of the energy matrix distribution to cover the electricity demand. The energy policy of a country depends on energy sources. In 2019, China's electricity consumption was 6,305 TWh, and the electricity generation source is 4,485,361 GWh, and most of it comes from coal. As a consequence, China's total Carbon Dioxide (CO₂) emissions are 9,258 Mt of CO₂. According to the United Nations (UN), sustainable development goals by 2050 all the countries worldwide should generate electricity through low carbon sources. The nuclear source helps to meet the growing demand for a clean and reliable low-carbon mix. China has 48 commercial nuclear reactors in 16 Nuclear Power Plants (NPPs) with an installed net capacity of 45,518 MWe. 11 nuclear reactors under construction while most NPPs are located in the South of the country. Heilongjiang Province has a coldest winter and lies in China's northernmost region where heating supply is as important as electricity supply that depend on coal, which can be replaced by nuclear power. The study focuses on a Nuclear Power Expansion (NPE) proposal in China to reduce CO₂ emissions and install power operation for a long-term process assessment.

1. INTRODUCTION

The energy matrix distribution of a country depends on its natural resources and the energy policies that the government wants to apply based on the demand for electricity that it is needed to cover. There are several sources of energy like wind, solar, hydro, coal, natural gas, biofuels, petroleum oil and nuclear. It is to the performance and capability to maintain a stable power source, it's what determines from which source the country rely on the natural sources for the production of electricity.

In the last decades, the economy in China has been developing speedily, and human activities grew as well as electricity needs. In 2019, China consumed around 6,305 TWh in the electricity market. [1]
Nevertheless, this progress in the economy brings as a consequence in the increment of CO₂ emissions due to human actions. China has emerged as the world's prime fossil fuel reserves user and CO₂ emitter, but simultaneously, to reduce its carbon-footprint, the country is trying to implement new strategies to mitigate these actions one of them is building the capacity of Nuclear Power. [2]

For decades, Nuclear has demonstrated to be a capable source of electricity. Its capacity could cover a massive demand for electricity production and establish a baseload power continuously. Nuclear energy is one of the most optimal technologies that reduce CO₂ emissions on the environment. [2]

Nowadays, nuclear energy produces 10% of the world's electricity from 442 reactors. [3] Nuclear has shown that it is the second-largest source of low-carbon power, and 31 countries generate their power based on nuclear, covering a total electricity demand of 391,685 MWe. [4] Referring to the Sustainable Development Goals (SDGs) established by the United Nations (UN) in its 2030 Agenda [5], nations around the globe implement nuclear science and technology to achieve and contribute their progress targets in fields including energy, food production, human health, environmental protection and water management. The applications of these fields contribute directly to the UN SDGs, specifically, goal 7 that focuses on "Affordable and clean energy" [6-7].

Yun Zhou (2011) emphasized that China's nuclear energy evolution is exclusive, and its effect on the worldwide nuclear market in the role as future supplier and customer is enlarging. [8-9] Xu tang (2015) wrote that national programs in China endorse significant impact on economic development, converting China into a "business world", but compromising environment and energy at a high cost. At a certain point, this rise and transition is also the foundation of China's economy, underlying regional harmony. China faces the challenge of reconciling its economy, electricity infrastructure and environmental stability. [10]

The objective of this study is to propose a strategy for the selection of nuclear reactor technology Generation IV for Nuclear Power Expansion (NPE) in China at Heilongjiang Province. This selection technique focuses mostly on the Analytical Hierarchy Process (AHP) establishing the model by prioritizing parameters dependent on the most relevant details for the evaluation of the assessment of low-carbon energy sources.

Section 2 provides a general overview, including areas to address in the energy sector and which factors are significant to consider in the low-carbon emissions assessment. Section 3 describes the data considered for the study, the methodology implemented and the model. Section 4 discusses the outcomes of this study. Lastly, section 5 contains the research limitations and future research directions; and the final part offers a few concluding remarks.

2. GENERAL OVERVIEW AND AREAS TO ADDRESS

2.1. Importance of Nuclear Energy in the Sustainable Development Goals

Availability of sufficient, secure and renewable energy is essential to achieving SDGs by mitigating hunger through health and education advances, encouraging economic growth and reducing greenhouse gas emissions. Nuclear power, like other technology, delivers electricity to ultimately achieve a high quality of life, nutritional health, a safe atmosphere and a prosperous economy. With nuclear technology, enhanced sewage facilities, well-functioning health care and education facilities, and efficient transport and telecommunications can be provided based on stable electricity. [6,11,12]
As specified by the International Atomic Energy Agency (IAEA), an open, inexpensive and renewable energy supply is key to the growth of modern society. Present scenarios expect a 1.5-3-fold rise in global demand for primary oil in 2050 compared to today and a 200 per cent relative increase in demand for power. [6,13]

The Harmony Program [13,14] aims for at least 25% of world energy to be produced by nuclear to reduce the carbon footprint impact on the environment. This primary goal can be achieved with the implementation of nuclear source since it has a reliable and safe performance among the other energy sources. [15]

As electricity demand continues growing, greenhouse gas emissions must decrease if we can mitigate climate change, and there must be a transition to cleaner sources to reduce air pollution. The transition involves more technology with low-carbon energy sources, and nuclear plays an essential role in this respect.

2.2. Current Situation in China and Heilongjiang Province

Over the past decades, China's economy has developed rapidly, and along with it, electricity consumption has grown. From 1990 to 2017, the country's energy usage rose from 580 to 6,302 TWh (Fig.1-A). This has made China the world's biggest energy user, responsible for one-quarter of the world's energy usage. [16]

However, with the growth of the economy, CO₂ emissions also increased. Over the period 1990–2017, CO₂ emissions in China increased 4.5 times — from 2,089 to 9,258 million tons, which is 30% of global CO₂ emissions.

Coal-fired power generates a significant part of greenhouse gas emissions, and it produces 70% of the electricity in China. [17]

The Total Primary Energy Supply of Electricity (Fig. 1-B) is still coming from Coal, which means not all the electricity production in China comes from sustainable energy sources. Coal produced 22,716.8 TWh while Nuclear Source produced 751.7 TWh in 2017, this means that Nuclear fuel is contributing to the energy portfolio, and it needs more efforts to play a crucial role in the energy flow balance of China covering more demand of energy [16].

![Figure 1. Energy in China](image)
Heilongjiang Province is an area located at the North-East of China. From the geographical description in the map in Figure 2-A, it can be seen that cities located in the Heilongjiang Province have a significant amount of CO₂ emissions between 500,001-1,000,000 Tons. It is important to visualize in Figure 2-B the location of the Nuclear Power Plants (NPPs) in China that no NPPs are planned in the Heilongjiang Province. [18]

![Spatial map of CO₂ emissions in China in 2012](image1)

![Nuclear Power Plants in China in 2012](image2)

**Figure 2. Heilongjiang Province Maps**

CO₂ emission is one of the key points why it is needed to implement more NPPs to mitigate the significant amount of CO₂ emissions. Several Provinces in China like Liaoning, Hebei, Hubei are planning to construct NPPs because these locations have high carbon emissions released to the environment because of the coal consumption (Figure 3) [19]. Urban areas of Heilongjiang Province are in the status as the provinces mentioned, and it is beneficial to consider the implementation of NPPs besides. [20]

![Coal Consumption in China](image3)

**Figure 3. Coal Consumption in China**
The coal consumption and the correlation of CO\textsubscript{2} emissions and economic growth appear in Figures 4-A and 4-B. It could demonstrate that coal consumption grows as the economic development, as Jin (2018) described the factors in his panel data analysis [22]. From 2003 it has been a considerable increment year by year in the coal consumption, it means in the coming years, the Heilongjiang Province discharges more carbon Emissions, and this creates an impact in the environment and human activities. [20]

2.2.1. Nuclear Energy Outlook in China and Heilongjiang Province

Currently, 4.9\% of the electricity production in China comes from nuclear power, and it has 49 nuclear reactors in operation and 10 units in construction; Figure 5 reflects this information. The total Net capacity is 45,518 MW(e). [23]. Among the net of nuclear reactors, China has several types as Pressurized Water Reactor (PWR), Pressurized Heavy Water Reactor (PHWR), Fast Breeder Reactor (FBR), and High-Temperature Gas Reactor (HTGR) [24].

PWR and PHWR belong to the category of Generation III Nuclear reactor Technology, while FBR and HTGR are in the Generation IV nuclear reactor. A well-proven and secure technology, the third generation PWR is the standard technology for nuclear power plants around the world and China's potential production of nuclear power. China would expand its expenditure in nuclear power plants in eastern coastal areas and create a nuclear power belt in eastern and central China, both of which operate by third-generation PWR. [25]

In 2020 the installed capacity of nuclear power plants, constructed or under planning, would be 58 GW and 30 GW respectively, whereas China's overall production of nuclear power is more than 5\%. In 2030, the planned capacity of nuclear power plants constructed or under construction rises to between 120–150 GW and 30 GW respectively, which increases China's overall nuclear power production by more than 10\%.

In 2050, the installed capacity of nuclear power, constructed or under construction, is expected to reach 200 GW.
power plants cross 350 GW, and China's nuclear share of China's overall production increases to 20 per cent, being one of the vital elements of the energy sector. [26, 27, 28]

China would become a nuclear power centre following the growth of nuclear power in the east and central areas of the country. China's nuclear equipment production and construction potential rise exponentially. [29]

Informed decision-making underpins the development of nuclear power and public acceptability limited the development of nuclear power. In future, the method of decision-making is more scientific and consistent to ensure clear definition and execution of nuclear development policies and plans. Regulations and laws ensure that all practices have a legal foundation. Positive advertisement and general guidance would enhance nuclear energy knowledge and public acceptability. [30, 31]

2.3. Low carbon electricity generation sources

China has now been the world's leading user of fossil fuel energy and CO₂ emissions and has carried out intensive research on the characteristics and driving forces of its carbon emissions and mitigation steps.

As the world's largest developed nation, with accelerated urbanization, industrialization and poverty reduction processes, China has strived to be the critical driving force caused by human activity in carbon pollution and their reduction. [23]

Fig. 6 shows that the electricity generation from Nuclear sources in China has been growing considerably, and it provides an optimal strategy to mitigate the effect of the Green House Gas (GHG) emissions. [32]

2.4. Nuclear power expansion for sustainability

Today, the principal driver of most of the energy policy is not economic but environmental, with concern about global warming. [33]

As economic growth continues in most of the countries, and the world population grows to over nine billion by 2040, increased global energy demand is inescapable. Consecutive reports of the International Energy Agency (IEA) World Energy Outlook,
Nuclear output is expected to increase by almost 80% in 2040 (Fig. 7). Several studies [36,37] indicate that the implementation of more NPPs brings more benefits in terms of economy, covering the demand for electricity and the public acceptance in China of Nuclear Power. China is the largest power market by far and poised for strong growth, making it a key determinant of global electricity trends. Coal is currently two-thirds of China's energy production but attempts are made to curb development and tackle deforestation and restrict carbon dioxide emissions. China is already the global leader in a wide array of low-carbon technologies and maintains this position: it accounts for 30-40% of the global market by 2040 for solar PV, wind, hydro and nuclear power. [1]

3. METHODOLOGY

3.1. Data

Before establishing a model in Super Decisions Software [38], it is significant to consider which goals or criteria to achieve and how to incorporate these criteria in the program. As described in the previous sections in the Nuclear Power Expansion Program, it is essential to consider the new trends and challenges in the nuclear industry. One of the main concepts that were introduced by NICE future [39] is the energy flexibility that considers the Nuclear energy system flexibility in three key ways: 1) Operations, 2) Productions and 3) Size for the current and future generations of reactors. Table I describes the main attributes that are needed to reach the base load power requirements in a Flexible Nuclear Energy System (FNES).

Table I. Beyond Base Load Power: Beyond Base Load Power: Nuclear Energy Systems New Reliability Attributes [39,40]

<table>
<thead>
<tr>
<th>Main Attribute</th>
<th>Sub-Attribute</th>
<th>Benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operational Flexibility</td>
<td>Manoeuvrability</td>
<td>Load following</td>
</tr>
<tr>
<td></td>
<td>Compatibility with Hybrid Energy Systems</td>
<td>Economic operation with increasing penetration of variable generation, alternative missions</td>
</tr>
<tr>
<td></td>
<td>Diversified Fuel Use</td>
<td>Economics and security of fuel supply</td>
</tr>
<tr>
<td></td>
<td>Island Operation</td>
<td>System resiliency, remote power, microgrid, emergency power applications</td>
</tr>
<tr>
<td>Deployment Flexibility</td>
<td>Scalability</td>
<td>Ability to deploy at the scale needed</td>
</tr>
<tr>
<td></td>
<td>Siting</td>
<td>Ability to deploy where needed</td>
</tr>
<tr>
<td></td>
<td>Constructability</td>
<td>Ability to deploy on schedule and budget</td>
</tr>
<tr>
<td>Product Flexibility</td>
<td>Electricity</td>
<td>Reliable, dispatchable power supply</td>
</tr>
<tr>
<td></td>
<td>Industrial Heat</td>
<td>Reliable, dispatchable process heat supply</td>
</tr>
<tr>
<td></td>
<td>District Heating</td>
<td>Reliable, dispatchable district heating supply</td>
</tr>
<tr>
<td></td>
<td>Desalination</td>
<td>Reliable, dispatchable freshwater supply</td>
</tr>
<tr>
<td></td>
<td>Hydrogen</td>
<td>Reliable, dispatchable hydrogen supply</td>
</tr>
<tr>
<td></td>
<td>Radios isotopes</td>
<td>Unique or high demand isotopes supply</td>
</tr>
</tbody>
</table>
If it is defined the sub-attributes of a FNES and it can be seen that the advantages of the system like the Compatibility with Hybrid Energy System because the system opens for more energy shares and distributes it in the energy matrix. The attributes of flexibility and robustness add higher impact and value for the power plant in scalability, siting and construction. Emphasizing these attributes brings more nuclear technology applications apart from electricity generation like district heating, desalination, hydrogen production and radioisotopes. [41]

The introduction and background of GEN IV was considered in Super Decisions' model like the specifications as Neutron Spectrum, Coolant, Temperature, Pressure, Size, and use or application to consider in the network implementation. The collection of the data in Table II and attributes help to make a pairwise comparison and find out the levels in the structure of the hierarchy. An efficiency assessment carries out using the Yoon method (2016) [39,42] and the IAEA Methods for the Assessment of Small and Medium Scale Reactors' for Economic Competitiveness (SMR). [43]

### Table II. Specifications of Six-Gen IV reactor technologies [44]

<table>
<thead>
<tr>
<th>Type</th>
<th>Neutron spectrum</th>
<th>Coolant</th>
<th>Temperature (°C)</th>
<th>Pressure</th>
<th>Size (MWe)</th>
<th>Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas-cooled fast reactors</td>
<td>Fast</td>
<td>helium</td>
<td>850</td>
<td>High</td>
<td>1200</td>
<td>Power &amp; Heat</td>
</tr>
<tr>
<td>Lead-cooled fast reactors</td>
<td>Fast</td>
<td>lead or Pb-Bi</td>
<td>480-570</td>
<td>low</td>
<td>20-180</td>
<td>Power &amp; Heat</td>
</tr>
<tr>
<td>Molten salt fast reactors</td>
<td>Fast</td>
<td>fluoride salts</td>
<td>700-800</td>
<td>low</td>
<td>1000</td>
<td>Power &amp; Heat</td>
</tr>
<tr>
<td>Molten salt reactor - advanced high-temperature reactors</td>
<td>thermal</td>
<td>fluoride salts</td>
<td>750-1000</td>
<td></td>
<td>1000-1500</td>
<td>Heat</td>
</tr>
<tr>
<td>Sodium-cooled fast reactors</td>
<td>Fast</td>
<td>sodium</td>
<td>500-550</td>
<td>low</td>
<td>50-150</td>
<td>Power</td>
</tr>
<tr>
<td>Supercritical water-cooled reactors</td>
<td>thermal or fast</td>
<td>water</td>
<td>510-625</td>
<td>very high</td>
<td>300-700</td>
<td>Power</td>
</tr>
<tr>
<td>Very high-temperature gas reactors</td>
<td>thermal</td>
<td>helium</td>
<td>900-1000</td>
<td>high</td>
<td>250-300</td>
<td>Power &amp; Heat</td>
</tr>
</tbody>
</table>

### 3.2. Methodological base

By the method of Analytical Hierarchy Process (AHP) and Analytical Network Process (ANP) [45] with the Nuclear Power Expansion process chart figure 8 was analyzed the model set up for the selection of reactor technology for the NPE. This is a common approach used in Systems Engineering. It was proposed in previous studies as Mark (2019) stated for the Selection of an Appropriate GEN IV Development Program [46] and Mosheni (2013) implemented in the Generation Expansion Planning (GEP). [47] AHP consists of four axioms, (1) shared judgements, (2) homogenous elements, (3) hierarchical systems or retroactive retroactivities and (4) order expectations. Suppose that n objects $A_1,...,A_n$, with known weights, $w_1,...,w_n$, etc. are defined, and conclude that there would be a matrix of pair ratios whose lines indicate the weight ratios of each object concerning all other items. There is then the equation: where the vector of weights $w$ is multiplied by $A$ on the right. This multiplication has resulted in $nw$.

Therefore, the dilemma, $A_w = n w$ or $(A - nI)w = 0$ must also be solved to retrieve the scale from the ratio matrix. [48] In Equation 1, a graphical representation is given.
This is a uniform linear equations system. The solution is nontrivial only when the determinant of $A-nI$ disappears, that is to say, $n$ has an eigenvalue of $A$. $A$ has the unit rank now since each row is multiple constants of the first row. So all of its values are zero for one. The sum of the matrix value, the sum of diagonal components, is equal to its trace, and the trace of $A$ is equal to $n$ in this example. So $n$ is the value of $A$, and a nontrivial solution is available. The solution consists of positive entries and is uniquely compounded. [49]

It uses ratio scales to collect all sorts of interactions to make detailed forecasts and make smarter decisions to support the analytical network process (ANP). Including clusters of related elements as desired, the ANP offers a detailed structure to analyze the mechanism from which ratio scale priorities are extracted from the allocation between elements and clusters. [50-53]

It is known the AHP has been used in studies capturing quantitative and qualitative criteria for balancing decision-making analysis. [54,55,56]

3.3. Model

The model established based on the criteria priorities like 1) Reduction of CO$_2$ emissions, 2) constant supply amount of electricity base on the electric output depending of the reactor technology (MWe), 3) Affordable energy related to SDG (mainly SDG7), and 4) the flexibility in base load power. Besides, it was considered the reactor alternatives from the 6 types of GEN IV.
proposed by GIF; and the design specifications mentioned in Table 2. Figure 9 contains the network model established for Super Decisions study, and the connection of the selected criteria mentioned previously. The AHP enables the analysis of project alternatives, defined by extremely heterogeneous assessment.

**4. RESULTS**

When it is selected several factors to compare in a weighted matrix in Super Decisions is significant to understand the geometry and the positions of the factors involved. From the calculation, it was obtained relative weighting to factors for individual criteria through the AHP. A future analysis proposes to make a definitive decision on the attractiveness of the NPE plan that the findings be mixed with a future budget review and stakeholder views on global variables. In this study are shown three Analytical Hierarchy Process Sensitivity Analyses. The main intention of this analysis is to estimate the behaviour of a Matrix and compare a priority with another set of criteria. For example, in this case, it was evaluated in the Matrix Row the Reduction of CO₂ emissions criteria, and it was compared as a priority to the Supply Constant Amount of Electricity, this information appears (in Figure 10-A).

From the graph in Figure 10-A can be read that VHTGR reactor type satisfies this comparison at 0.254 value or 25.4% among the other reactor types. In this sensitivity analysis, VHTGR shows a viability strategy of future reactor technology to implement in the energy matrix distribution. In the same graph appears several intervals with peaks near to the 0.6 normalized value which favours VHTGR reactor type.

In the case of study 2, it has been compared to the Supply Constant Amount of Electricity as a Matrix and selected the priority of Affordable Energy in the matrix’s values for weighted factors, which satisfies the SDGs in the qualitative analysis. Figure 10-B shows the analysis. VHTGR again represents a higher capability among the other technologies to satisfy this comparison with 25.4% of reliability in the AHP analysis. The figure shows several intervals. It describes how it has been simulating the probability that this system works in the range of 0 to 1 for the experiments. Once the experiment normalized the data, the VHTGR alternative satisfies around 30% of the matrix row of Supply Constant Amount of Electricity vs. Affordable Energy in the analysis.

As a third AHP Sensitivity Analysis, Figure 10-C contains the comparison between the Matrix row set for the Supply Flexibility in base load power versus the Priority of Affordable Energy (SDG7). Earlier studies demonstrate how affordable energy achieves all the 17 SDGs. [6, 57, 58]. The analysis is consistent with the previous ones because once more, the VHTGR shows better
performance in the sensitivity analysis. The schematic picture shows that around 75% of the data analysis is normalized, and it comes from VHTGR alternative.

From the previous studies the AHP, VHTGR seems to be the most optimal option to implement in the diversification of the Nuclear Scenarios to reduce the CO₂ emissions. However, just to analyze deeply, it is described in the ANP analysis for the Main Goal about the Selection of Reactor Technology for a NPP and the investigation of the proposed criteria. Figure 10-D shows the ANP Sensitivity Analysis for the main goals and criteria selection, from the results could be seen VHTGR satisfies all these attributes.

Figure 10-D has the bar charts for the four proposed criteria established in section 3. In the criteria C1) the VHTGR shows a lower probability in comparison with the other technologies because it just satisfies 0.148. In the other side, criteria C2), C3) and C4) present a high probability of 0.267, 0.259 and 0.277 respectively. Seventy-five percent (75%) criteria were satisfied through the ANP analysis.

![AHP Sensitivity Analysis 1](image1)

![AHP Sensitivity Analysis 2](image2)

![AHP Sensitivity Analysis 3](image3)

![ANP Sensitivity Analysis for Goal and Criteria selection](image4)

**Figure 10. Sensitivity Analyses**
Figure 11-A contains the overall priorities for the alternatives proposed in this study. From the summary, the ideal case to implement is VHTGR in the decision-making process of the Nuclear Power Expansion to achieve the SDGs. Figure 11-B describes all the priorities selected in this study, and it highlights the 1) Reduction of CO$_2$ emissions is the main priority followed by 2) Supply Constant Amount of Electricity and 3) the VHTGR; among all the factors, these three priorities show more impact in this study. These factors might be considered as significance criteria in the decision-making process for the NPE.

![Synthesis of the leading network](image)

**Figure 11. Priorities in Super Decisions**

5. CONCLUSION

The research analyzed the NPE in Heilongjiang Province intending to reduce CO$_2$ emissions and install power operation for a long-term process assessment. The authors consider the benefits of nuclear technology and its importance for diversifying the energy portfolio in China to meet the SDG7. The study offers an AHP and ANP implementation strategy as a feasible solution for a nuclear power plant proposal for GEN IV technology deployment in Heilongjiang Province, which is a region that has not considered yet in the national nuclear expansion program in China.

According to the results obtained in the sensitivity analysis for AHP and ANP, it has been found that VHTGR technology satisfies most of the proposed criteria for this study. The criteria that were listed in this case are 1) Reduction of CO$_2$ emissions, 2) Supply a constant amount of electricity, 3) Affordable energy (SDG7), and 4) Flexibility in base load power. These considerations were taken into account in the analysis carried out by Super Decisions Software to identify which reactor technology could be better to propose for the NPE at the Heilongjiang Province. It should be remembered that the proposed technology will contribute to the low-carbon emission assessment to follow the Energy Policies Scenarios in China. By 2050, at least 25% of global electricity produced is to come from Nuclear Source, as discussed earlier than 10% of the nuclear energy industry.

Some limitations exist in this research. First, the research is limited to one Chinese province-Heilongjiang. Second, the research data period is limited between 1990-2016. Thirdly, since
GEN IV technology is not fully deployed around the world, there are no more attributes to include in the model to measure the performance of the technology. The authors also plan to continue collecting social, economic and environmental data from the Chinese provinces to analyze nuclear development from the historical perspective and how nuclear development has impacted sustainable country growth.

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